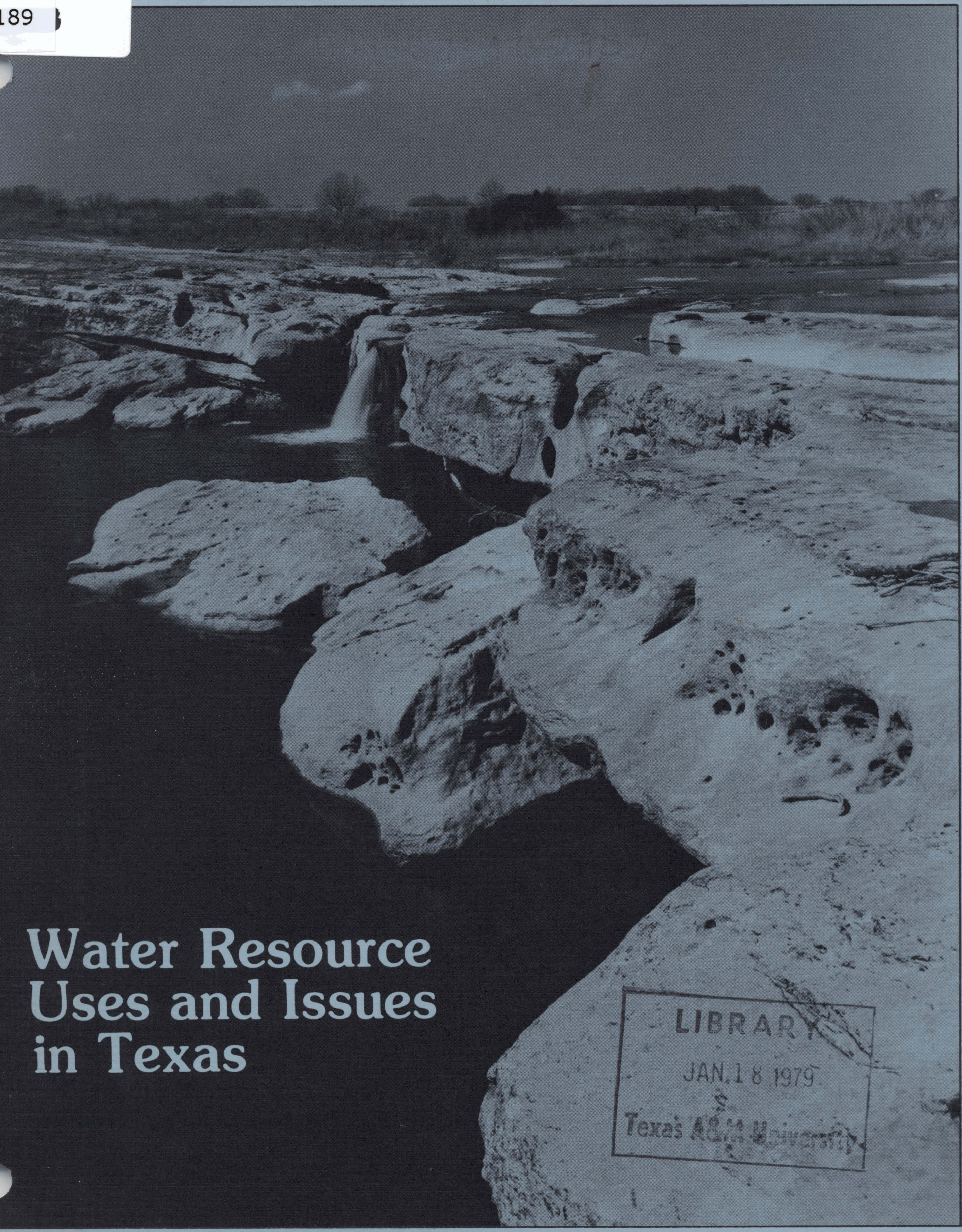

Water Resource Uses and Issues in Texas

The Texas A&M University System • The Texas Agricultural Experiment Station • Neville P. Clarke, Director, College Station, Texas

Acknowledgments

This study of the Texas water situation completes a series on natural resource use in the State. The series includes four publications of the Agricultural Experiment Station written by John G. McNeely and Ronald D. Lacewell of the Department of Agricultural Economics. They were edited by and graphic designs created by members of the Department of Agricultural Communications. The four publications are:

May 1975 - MP-1190: *Rural Land Resource Problems . . . A Need for Planning*

November 1976 - B-1166: *Flood Plain Management*

May 1977 - B-1177: *Surface Water Development in Texas*

August 1978 - B-1189: *Water Resource Uses and Issues in Texas.*

The present publication considers the implications of ground-water overdrafts and impending full utilization of surface-water resources in Texas. Principal source of information was the Texas Department of Water Resources, which has responsibility for continuing analyses of current and future water development and use in Texas. Dr. Herbert W. Grubb, Director of Planning and Development, was especially helpful in providing data revisions for river and coastal basins. Mr. Micky Walker made available to us the graphic data and picture file of the Department.

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Drs. Bruce Beattie and Lonnie Jones assisted with all publications in the series by their review of manuscripts, editorial comments, and continued interest and encouragement. But, of course, any error, omissions, or other deficiencies in the report are the sole responsibility of the authors.

Photographs courtesy of

High Plains Underground Water Conservation District — pages 12, 29, and 40.
Texas Department of Water Resources - pages 9, 18, 24, 34, and 47.
Texas Parks and Wildlife Department - page 49, cover, and title page.
Dr. William M. Lyle, Halfway, Texas - page 44.

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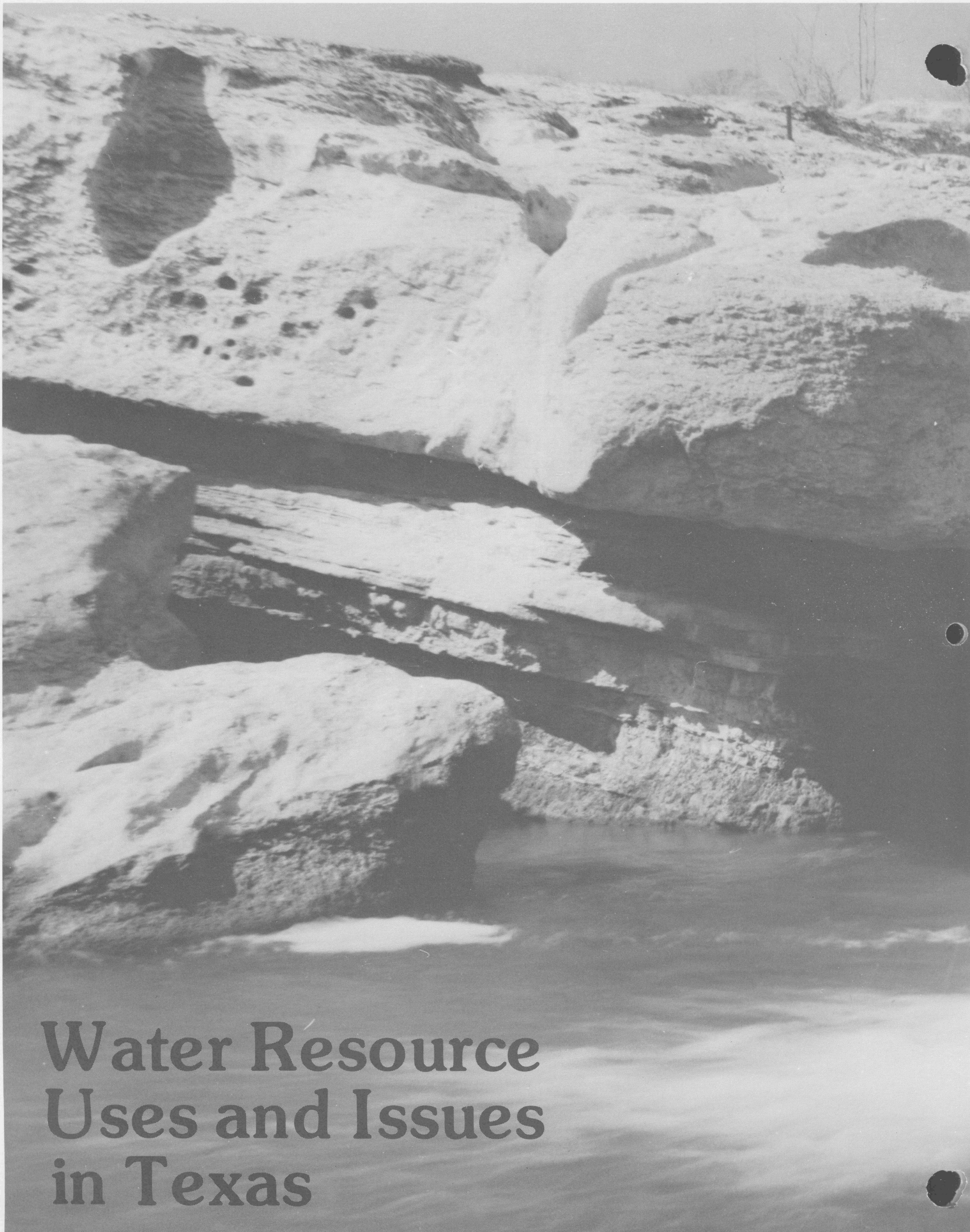

Water Resource Uses and Issues in Texas

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Summary

Texas has a long-term annual availability of fresh water from ground and surface sources combined of at least 14.1 million acre-feet (maf), according to the Texas Department of Water Resources. This includes a safe ground-water yield of 5.1 maf, defined as the quantity of average, annual, recoverable recharge to ground-water aquifers. It also includes a firm surface water yield of at least 9.0 maf, defined by the Department as "the quantity of water that can be withdrawn or released from reservoirs continuously, on an annual basis, over periods of time of sufficient length so as to span the most severe period of drought in the reservoir catchment areas." (50)

The ground-water use for all purposes in Texas in 1974 was 12.2 maf. This amount exceeds the safe ground-water yield by 7.1 maf and is accomplished by removing more ground water than is replaced by natural recharge. This annual ground-water overdraft is lowering water tables, increasing pumping costs, and affecting the physical characteristics of individual aquifers.

A landowner in Texas owns the ground water beneath his land and has the right to drill wells and appropriate all of the underground percolating waters generally without regard to the effect upon other landowners. The general opposition to control of individual ground-water rights at any level, be it federal, state, or local, effectively limits the initiation of comprehensive management programs. A law was enacted in 1949 authorizing creation of underground water conservation districts. Any area in Texas can be included in a district if it has substantial ground-water resources, if its boundaries can be determined within the terms set out by the law, and if its people vote to form a district. Most districts have directed their efforts toward prevention of waste, well recharge, conservation education, and data gathering on water table levels. They have not regulated the production of water from wells directly. The districts are responsible for granting permits for new wells. Typically, some minimum spacing between wells is required.

The Ogallala Aquifer supplies the Texas High Plains with nearly all of its water for irrigation, municipal, and industrial uses. The amount of ground water used in this area in 1974 was estimated at 8 maf, which was 78 percent of the ground water used in the State in that year. In some areas the saturated thickness of the aquifer is less than 50 feet; in other areas it is more than 500 feet. In the thinner sections where the aquifer is essentially depleted, irrigated cropland has been converted to dryland farming or is being returned to grasses. At projected rates of use, the present ground-water supplies in much of the Southern High Plains area are expected to be depleted to the point that they will not support irrigation by the year 2000. Supplies of the northern area, however, may support widescale irrigation to 2040 or longer.

The Ogallala underlies much of the Great Plains, and its exhaustible nature is a problem throughout. The Water Resources Development Act of 1976 authorized a multi-state and Federal study of the Ogallala Aquifer. The study is to evaluate opportunities to more effectively use the ground water and includes planning to increase water supplies. A final report with recommendations will be transmitted to Congress no later than July 1, 1980.

The extensive development and use of the Gulf Coast Aquifer have created some difficulties. Problems have included declining water levels, land surface subsidence, salt water intrusion, and water quality impairment from surface and subsurface disposal of wastes. Increasing costs of ground-water supply are not shared equitably by all the ground-water users in the area. Choices must still be made as to the extent and purpose of future use and the appropriate federal, state, and local responsibilities.

In 1975, the Administrator of the Environmental Protection Agency was petitioned to designate the Edwards Aquifer as a sole-source aquifer under the provisions of the Safe Drinking Water Act. About 90 percent of the recharge of the Edwards Underground Reservoir is from streams that cross areas where the aquifer crops out or is near the land surface in the Balcones Fault Zone. Population growth on the recharge zone has increased greatly over the past 10 years and reflects the urban expansion of metropolitan San Antonio. The Environmental Protection Agency has established procedures for reviewing commitments of Federal financial assistance to development projects in the San Antonio area. Projects which may contaminate the aquifer so as to create a significant hazard to public health will be disapproved for funding.

The two basic doctrines of surface-water rights recognized in Texas are the riparian doctrine and the appropriation doctrine. The corresponding water rights perfected under these doctrines are commonly referred to as riparian rights and appropriative rights. The riparian right is a common law right to use a proportionate part of the normal flow of a stream as a part of the ownership of lands abutting the stream. The appropriative right is an acquired right under a procedure provided by statute to divert from a water supply a specific quantity of public water under a permit granted by the Water Rights Commission.

Surface water may be classified as diffused surface water or as water within a defined watercourse. Diffused surface water originates as rain, snow, or sleet and continues to be surface water until it reaches some natural channel or watercourse. Once it reaches a watercourse, it becomes part of the stream and is the property of the State, subject to the rights of owners of riparian lands and those who have obtained appropriative rights.

At the end of December 1976, the Texas Water Development Board reported authorized and claimed amounts of water in water courses of 56.9 maf. Most existing permits claim water for irrigation, although some of the largest are for municipal and industrial use or for hydroelectric power generation. Actual use of surface water in watercourses in 1974 was 5.1 maf. The Water Rights Adjudication Act was passed in 1967, and adjudication of water rights is currently in progress. The Water Rights Commission expects adjudication to be completed in the next 10 years at which time certificates of adjudicated water rights will be issued to successful claimants.

When water falls from the atmosphere as precipitation, it becomes diffused surface water until it reaches a channel or watercourse. In Texas, it is established that landowners generally have the right to intercept and use diffused surface water on their land so long as the reservoir does not exceed 200 acre-feet in capacity. Since 1953, water in these small reservoirs may be used only for domestic or livestock purposes. A permit is required from the State if the dam is on a stream course, if storage exceeds 200 acre-feet, or if the water is put to other uses. Downstream water users usually are of the opinion that such small reservoirs and related conservation land treatment have the effect of reducing their water supply. It has been calculated that near El Paso, a watershed of 24,000 acres is required, under normal conditions, to supply a 200 acre-feet reservoir; 10,000 acres on the High Plains; 2,400 acres in Central Texas; and only 600 acres in East Texas. Many small impoundments are quite shallow with large surface areas compared to storage capacity. Losses of water are heavy from evaporation, transpiration by vegetation, seepage, and percolation.

The amount of surface water available for distribution is determined by the magnitude and distribution of the annual precipitation, the proportion of the precipitation that reaches the watercourses, and the availability of reservoir storage. Reservoir storage provides the ability to change allocation of water over time. Excess water from wet periods can be held and then released for use in dry periods. This reallocation may occur within a given year or over a period of several years. The firm yield for a reservoir can be expressed as the maximum amount of water that can be supplied continuously by a reservoir under conditions of the driest and most severe drought period known to have occurred at that site. Firm yield is decreased by net loss of water by evaporation from the reservoir surface, by leakage, by seepage or infiltration, and by evapotranspiration from adjacent ground and vegetation. Firm yield is reduced each year the reservoir is in operation as the initial conservation storage capacity is depleted by sedimentation.

Conservation storage capacities and contents yield differently in different parts of Texas. In humid East Texas, a reservoir may provide a firm yield equal to or larger than its conservation storage capacity. In subhumid Central Texas, a reservoir may provide a firm yield equal to only one-fifth or less of its storage capacity. In semiarid and arid West Texas, a reservoir may provide a firm yield varying within a range equal to one-tenth to one-thirtieth or less of its conservation storage capacity. Detailed studies are necessary to provide reliable estimates of the true water supply potential. Conservation storage capacity for all reservoirs in Texas of more than 5,000 acre-feet was reported to be 30 maf by the Water Development Board in April 1976. The Texas Department of Water Resources in June 1978 estimated firm yield of surface water projects at 9.0 maf based on development existing in 1974.

The Texas Gulf Coast has ten estuarine systems scattered from Louisiana to Mexico. They vary considerably in size, volume, use, accessibility, commercial importance, and ecological characteristics. Estuaries are semi-enclosed coastal bodies of water that have a free connection with the open sea and within which sea water is diluted with fresh water from land drainage. Human use of estuaries includes such activities as industrial water supply, transportation, commercial fishing, waste disposal, recreation, and mineral extraction. Nature uses estuaries and surrounding areas as aquatic nurseries and wildlife and fish habitats. Estuaries play a vital role in the life cycle of an estimated 65 percent of the nation's marine fisheries. Human modification of fresh-water inflow commonly impairs biological functions of an estuary.

The State Legislature in 1975 made State policy "the maintenance of a proper ecological environment of the bays and estuaries of Texas, and the health of the related living marine resources." Comprehensive studies were called for, and the Water Development Board contracted with the Remote Sensing Center of Texas A&M University for a 1976 season-long remote sensing study of certain critical river deltas along the Central Texas Coast. The studies are continuing and are to be completed and results published by December 31, 1979.

All of the wetlands study areas have been impacted by man's activities, but in varying degrees. Some are deteriorating; others are recovering from earlier construction activities. If periodic flooding of deltaic wetlands is inhibited or prevented entirely by construction activities, the value of maintaining a particular level of fresh-water inflow into the estuaries is unclear. Dredging and spoil deposition appear to be the greatest, single, damaging mechanism in the Texas Coastal wetlands.

The Legislature is expected to make some basic policy decisions concerning the estuarine resources. As development continues, choices will be made. The commercial harvest of fishery resources is greater in value from Texas than from any other Gulf State. Recreation and tourism associated with these estuarine systems generate more than $5 billion annually. The Texas Department of Water Resources estimates that the annual gaged river inflows needed to sustain major estuarine systems is 6.1 maf. Permanent damage already has been done to some Texas Gulf estuarine systems. The damages will escalate and become irreversible unless positive and comprehensive action is taken.

Agriculture, in contrast to manufacturing and most other uses, consumes a large part of its water withdrawals. There is less return flow to the water source from agriculture and less water available for reuse. The value in use of irrigation water tends to be low compared with municipal and industrial uses. Irrigated crop agriculture in Texas has been and will be limited by the volume and cost of available water. Costs are affected by the depth to water, the efficiency of the aquifer in yielding water, and the costs and efficiencies of energy, power, and equipment used.

Estimates of the future population of metropolitan areas in Texas indicate a continued rapid growth. The costs of providing metropolitan water services have escalated rapidly. Yet, some metropolitan water managers anticipate a continuing increase in daily per capita use of water. The National Water Commission considers that the primary metropolitan objectives are (1) to provide the three basic water services — water supply, wastewater collection and treatment, and storm water management — efficiently and effectively; (2) to make efficient use of scarce water resources; and (3) to lessen the disrupting and degrading effect of urban growth and development on the urban environment and water quality. When water system facilities are built and operated with enough foresight, many social benefits can accrue to balance the costs of the facility. Recycling or reclaiming wastewater has great potential for increasing the amount of water available for use. Increasing the price of water may complement other measures taken to improve efficiencies.

In planning for efficient water use, precipitation and drought are basic considerations. Mean annual precipitation ranges from less than 8 inches in extreme West Texas to more than 56 inches in extreme East Texas. Generally, rainfall increases from west to east across Texas, with the average increase being about 1 inch every 15 miles. Drought interrupts the flow of water supplies and increases the consumption requirements from water in storage. People can cope partially with drought by drilling additional wells or by constructing surface-water storage facilities and storing surface-water supplies for emergency use. Longer droughts tend to require water conservation measures by all users.

When a drought occurs, streamflow decreases, ground-water levels decline due to increased pumping, reservoir storage is depleted, and water quality is degraded. One of the most critical problems is a lack of sufficient water in the stream to flush and dilute contaminants in the channel. Lack of oxygen can be lethal to fish and other aquatic life, cause odor problems, and decrease a stream's natural ability to purify itself. Generally, the shallow water created by low streamflow becomes warmer than usual. Evaporation increases, which further decreases the limited supply of surface water.

Local initiative is the key to drought management. The weight of responsibility on local officials and individuals is great. Success of programs to conserve water depends upon how well the full participation of the public is motivated and achieved. Water users must believe that they are fairly treated, that everyone is asked to save, and that sacrifices are felt proportionately. Experiences in Western states in 1976 and 1977 indicated that effective conservation programs can reduce water use as much as 50 percent without undue hardship.

Minimizing the effects of future droughts requires more efficient use of existing water resources. Some supplies that are being utilized cannot be replaced. Other supplies of water can be predictable in quantity, quality, and location. Skillful planning is required to evaluate tradeoffs among competitive users. The chief problem is overcoming the habits and traditions of industries, farmers, and homeowners who demand the continued availability of cheap and plentiful water. There is a compelling need to reform the institutional incentives to waste water. Methods for increasing efficiency in water use include water rights reform, rationing, mandated conservation practices, pricing strategies, and technological development. Economic realities can provide the most effective limits to further growth in water-deficient areas.

The development of Texas has exacted a high price in the deteriorating quality of its water resources. Rivers, lakes, and coastal waters have been heavily damaged by the discharge of waste, by polluted runoff from urban, agricultural, and resource development and by accelerated erosion and sedimentation. A strategy to achieve cleaner waters and reduce the production of unnecessary pollutants is now under way. The objective of the Federal Water Pollution Control Act of 1972 is to restore and maintain the chemical, physical, and biological integrity of the Nation's water. Each state is required to identify and locate all point sources of pollution such as sewage plant outfalls. Also, the State must locate all man-created nonpoint source pollution loads such as soil erosion and set forth procedures to control these discharges where feasible. One result will be expanded reuse of return flows when waste treatment is accomplished.

Return flows are listed by the Department as a separate water supply source for basins. Municipal and industrial uses provide 2.2 maf and irrigation provides 0.8 maf. Location of return flows determines the potential for subsequent reuse or for flow through the river basin to the estuarine area.

Introduction

In the past, Texas citizens usually were able to live wherever they chose without concern for the availability of water. Where other resources were available, a water supply also was generally readily available. The purpose of this report is twofold — to review the current status of water resources in Texas relative to institutions and incidence of availability and use and to address some important water resource issues facing the State. Water resources to meet agricultural, municipal, industrial, and residential demands are taken from ground-water and surface-water sources.

Ground Water

Ground-water supplies are obtained from both reserves and annual sources. Ground water pumped from closed basins or slowly recharged aquifers like the Ogallala represents depletions of a reserve or stock resource. Pumping from aquifers that are readily recharged from infiltration and percolation of precipitation or deep percolation from streams, reservoirs, canals, or irrigated land constitutes the utilization of an annually renewable or flow resource. The Edwards Aquifer is an example. The ground-water supply available in any given year in Texas represents the sum of the yields obtained from the renewable sources plus the depletion of the stock resource deemed desirable by land owners who own the ground water beneath their land.

Ground-water aquifers supplied about 71 percent of the water used in Texas in 1974. Rural inhabitants, irrigators, municipalities, and industries generally have turned to this source because of its widespread availability and its relatively low development and pumping costs. By contrast, surface-water supplies are not available, or the costs for constructing facilities for storing, treating, and distributing surface water are high (30).

Although Texas courts recognize both percolating water and underground streams as ground water, such water is presumed to be percolating unless it can be proved to be a recognizable underground stream with defined channels. The courts have held that the owner of land is the absolute owner of percolating water beneath his land. As land owner, he can withdraw the percolating water beneath his land at the rate he chooses and for whatever purpose he chooses. Neither an injured neighbor nor the State can effectively exercise control over water-use practices involving ground water, except where local underground water districts have been formed. This is in direct contrast with the extensive and direct involvement of the State in controlling surface-water supplies (30).

In 1949, Texas passed a local option ground-water control law. Under this law, local underground water districts can be formed to carry out ground-water management including regulation of the withdrawal of ground water. Any area in Texas can be included in a district if it has substantial ground-water resources, if its boundaries can be determined within the terms set out by the law, and if its people vote to form a district. Although a few districts have been formed under this law, they have not made any effort to regulate directly the production of water from wells (30).

Ground water is being removed in many areas of the State more rapidly than it is being replaced by natural recharge. In effect, the resource is being mined. The mining of ground water is especially critical in those areas where ground water constitutes the only source of suitable water supply. The Texas Water Development Board[1] estimated the annual natural recharge rate for all of the Texas River Basins to be 5.1 maf in 1974. Withdrawals of ground water were estimated by the Board to be 12.2 maf in that same year. This annual ground-water overdraft of more than 7.1 maf is lowering the water tables, increasing pumping costs, and affecting the physical characteristics of individual aquifers.

Surface Water

Surface water supplied 5.1 maf or about 29 percent of the water used in Texas in 1974 according to the Texas Water Development Board. Surface-water use was considerably below the firm yield of surface-water projects of river and coastal basins of 9.0 maf. Also available for use in some locations were return flows from municipal, industrial, and irrigation uses that amounted statewide to 3.0 maf. This figure does not include the surface water that made its way to the Gulf. Annual precipitation ranges from 8 inches or less in far West Texas to more than 56 inches in far East Texas near Orange. Texas is also subject to wide fluctuations in rainfall from year to year. Precipitation often varies more than 50 percent from calculated averages, and in most years, will be below the annual average. The State is subject to periods of drought, sometimes of long duration. About three-fourths of the runoff in Texas originates in the eastern one-fourth of the State (32).

The two basic doctrines of surface-water rights recognized in Texas are the riparian doctrine and the appropriation doctrine. The riparian right is a common law right to use a proportionate part of the normal flow of a stream as a part of the ownership of lands abutting the stream. The appropriative right is an acquired right under a procedure provided by sta-

[1]By a legislative act, the Texas Water Development Board, the Texas Water Rights Commission, and the Texas Water Quality Board were merged into the TEXAS DEPARTMENT OF WATER RESOURCES, effective September 1, 1977.

tute to divert from a water supply a specific quantity of public water under a permit granted by the Texas Water Rights Commission (32).

Texas courts and State water agencies have experienced great difficulty in trying to correlate the riparian and appropriative water rights which exist side by side on the same stream. Several attempts have been made to define or quantify the nebulous riparian rights so that all existing claims to or use of surface water could be inventoried, thus allowing more effective water resource management. Authorized or claimed amounts of water for all basins and for all purposes amounted to 56.9 maf at the end of 1976, according to the Texas Water Development Board. It is expected that several more years will be required to complete the process of adjudication and to establish Texas surface-water rights (32).

Another major use of surface water is for estuarine systems spread along the Texas coastline. The systems involve more than 1,400 miles of intricate shoreline, and associated recreation and tourism generate more than $5 billion annually. Virtually all coastal fishing resources are dependent upon the estuaries, and the productivity of the estuaries is dependent upon the quantity, quality, and timing of fresh-water inflows (50).

In view of established State and Federal legislation, the Board's objective in coastal management is to assure that sufficient quantities of fresh-water inflow are seasonally provided at appropriate geographic locations to maintain Texas estuarine environments at optimum sustainable levels of productivity. The Board estimates preliminary sustaining annual gaged river inflows of 6.1 maf, which are suggested as statistical long-term averages needed to sustain the estuarine system (50).

The importation of water to Texas has been considered a possible way to offset future deficits in available water supplies. At a public meeting in Lubbock, Texas on April 12, 1973, Mr. Norman Flaigg, Texas Area Engineer for the U. S. Bureau of Reclamation released the findings of the "West Texas and Eastern New Mexico Import Reconnaissance Report." The project was estimated to cost several billion dollars. It was found to be physically feasible but economically infeasible.

"Irrigators have a payment capacity adequate to cover less than a fifth of the annual payment requirements.

"Using primary benefits only, the project is only about one-seventh justified. With primary and secondary benefits derived according to Bureau of Reclamation procedures, the project is only about one-fourth justified." (21).

Section 193 of the Water Resources Development Act of 1976 authorizes a comprehensive study of several states relying on ground water from the Ogallala Aquifer. The study will evaluate both interbasin transfers of water and opportunities to more effectively and efficiently use available supplies.

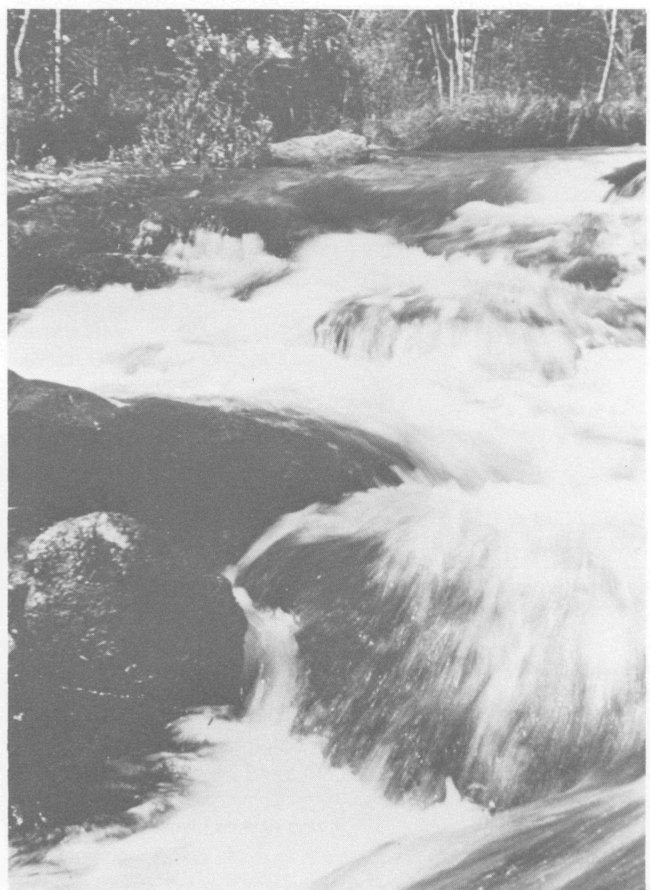
Water Planning Responsibilities

In 1965, the 59th Texas Legislature assigned the Texas Water Development Board the responsibility for preparing and maintaining on a current basis a comprehensive statewide water plan. This plan is to serve as a flexible guide for the orderly development of Texas water resources for the ensuing 50-year period. The planning horizon for a current updating of the Texas Water Plan is the year 2030. The specification of the 50-year planning horizon is required to comply with the legislative requirement that the basin of origin of any surplus surface waters shall have its projected 50-year water requirements protected from transfer out of the basin except on an interim basis (50).

Planning Areas

Texas water-planning legislation specifies that the planning areas within the State shall be the river basins and coastal basins drainage areas. These are the State's surface-water natural drainage areas. Surface water surplus to the 50-year projected in-basin needs can be exported to basins of shortage subject to the conditions that the beneficiaries of such imports shall pay the development and importation costs (50).

Texas has 15 river basins and 8 coastal basins (Figure 1). Each basin is designated as a planning area for purposes of calculating in-basin water supplies and for projections of the 50-year foreseeable future in-basin water requirements. The river-basin areas were delineated through the use of topography so that each part of the State is assigned to its appropriate drainage basin. The effective water supply of a river-basin area at a given time was defined as the



Water planning and efficient water use are vital to the Texas economy.

sum of safe yields from ground-water aquifers at that time and the firm yield of existing reservoirs at that time (50).

Water Yields

Safe ground-water yields, on an annual basis, are defined as the quantity of average annual recoverable recharge that is returned to the ground-water aquifers located in the planning area. Depletion of ground-water resources is continuing from several major aquifers substantially beyond safe ground-water yields. The ground water is privately owned by holders of the surface estate. Planning with regard to ground water is minimal in most river basins and coastal basins (50).

Firm annual reservoir yield is defined by the Board as "the quantity of water that can be withdrawn or released from a reservoir continuously, on an annual basis, over periods of time of sufficient length so as to span the most severe period of drought in the reservoir catchment area." This most severe period of drought is designated as the critical period during which there will be insufficient storm or flood flows that can be impounded in reservoirs to replace water that is withdrawn by users. Firm yields depend upon factors including precipitation, runoff, evaporation, and reservoir capacity (50).

Safe yields of ground-water aquifers and firm yields of reservoirs have been calculated for each river-basin planning area using historical and current data. Potential reservoir sites have been located and evaluated as to potential firm yield, subject to the

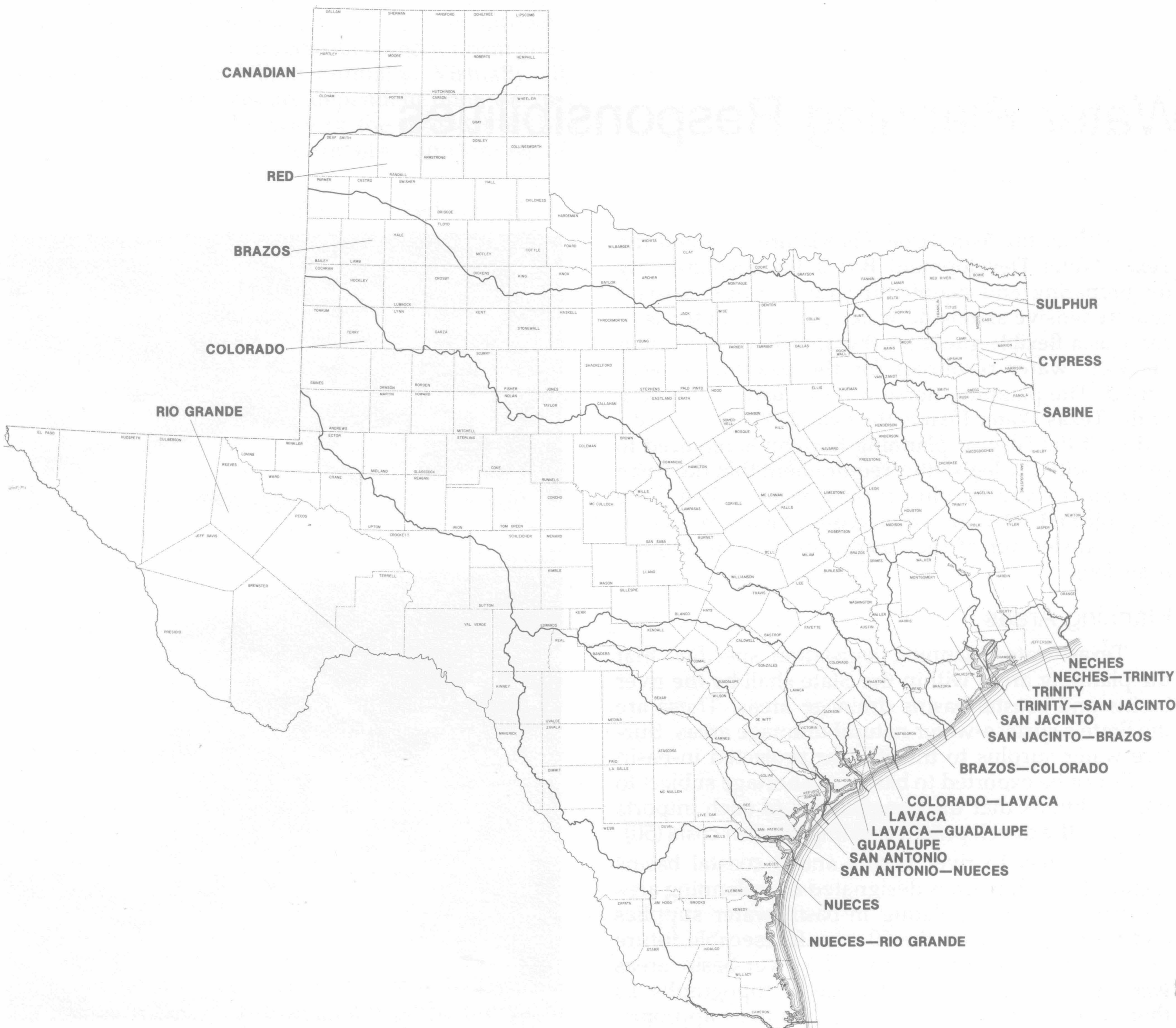


Figure 1. River and Coastal basins of Texas.
Source: Texas Water Development Board.

location of other reservoirs and relevant operating procedures. Projections of water requirements and present and potential water supplies have been made, permitting determination of the water-supply balance for each basin over the 50-year period. Any excess above that needed to meet requirements of the 50th year, subject to all existing water rights, can be considered as surplus to the basin needs and available for export to meet the needs of basins having a projected deficit (50). Table 1 shows the groundwater and surface-water renewable resource by basins. Available water as shown in this table excludes fresh-water inflow into the estuarine systems.

Environmental Constraints

The Federal Water Pollution Control Act amendments of 1972 have the stated objective "to restore and maintain the chemical, physical, and biological integrity of the Nation's waters." That law, known as P. L. 92-500, declares unlawful the addition of any pollutant to navigable waters from any point source. Navigable waters include tributaries of navigable waters, interstate waters, and most intrastate lakes, rivers, and streams (17).

P. L. 92-500 contains numerous other controls on the use of water generally by industry, agriculture, and the public. Water-quality standards under Section 303 (c) and the planning requirements of Sections 208 and 303 (e) force state and local agencies to defer to the Environmental Protection Agency (EPA) in regulating water use. Section 404 authorizes the Army Corps of Engineers to issue permits for the discharge of dredge or fill material into the navigable waters at specified disposal sites. This section also directs the Administrator of EPA to develop guidelines for disposal sites. It allows him to prohibit or limit the use of any area as a disposal site if the proposed discharge will have adverse environmental effects (17).

As now written, Section 404 resurrects and adds strength to the Fish and Wildlife Coordination Act of 1934. This law requires a federal construction or licensing agency, such as the Army Corps of Engineers, to consult the U. S. Interior Department and state wildlife resource agencies to prevent damage to wildlife resources from water development projects. This is the basis for the U. S. Fish and Wildlife Service's demand for mitigation lands at several Texas reservoirs (17).

The purposes for which available water may be sought often conflict. Environmental purposes are achieved for the most part by assuring minimum stream flows for fish and wildlife, recreational use, pollution dilution, and estuary replenishment. Many uses of water are classified as in-stream uses. Natural stream flows are used not only for environmental purposes but for navigation, hydroelectric power, and other purposes that are mainly non-consumptive in nature. The maintenance of in-stream flows at minimum levels is designed to preserve the biological and recreational values of a stream. Estimates of flow requirements are crude. On some rivers, minimum flow needs, combined with other uses, already exceed the water supply (55).

Current water-use rates relative to the ground and surface water resources available on a sustained annual basis suggest that Texas is a water-deficit state. Because current use rates are being met by ground-water mining, water planning and efficient use are critical issues, and limitation of the water resource is an important factor to the State's economy. If growth in population and economic activity continue, it will be necessary to adjust to lower per capita levels of water usage.

TABLE 1. ANNUAL RENEWABLE GROUND AND SURFACE WATER SUPPLY FOR TEXAS, BY BASINS[1]

Basins	Ground Water Natural Recharge	Surface Water Yield from Runoff
	------------000's of Acre-Feet[2]------------	
Canadian River	90.6	103.0
Red River	348.0	415.6[3]
Sulphur River	12.7	180.0[4]
Cypress Creek	249.5	246.5
Sabine River	243.2	1,064.4[5]
Neches River	566.7	1,277.1[6]
Neches-Trinity Coastal	11.0	0
Trinity River	247.0	1,657.0
Trinity-San Jacinto Coastal	42.0	0
San Jacinto River	337.0	242.8
San Jacinto-Brazos Coastal	110.5	0
Brazos River	518.8	789.5
Brazos-Colorado Coastal	68.0	0
Colorado River	574.2	776.2
Colorado-Lavaca Coastal	8.0	0
Lavaca River	86.0	0
Lavaca-Guadalupe Coastal	48.0	0
Guadalupe River	125.8	85.0
San Antonio River	355.1	39.2
San Antonio-Nueces Coastal	30.0	0
Nueces River	222.9	252.0
Nueces-Rio Grande Coastal	115.0	0
Rio Grande River	720.3	1,833.4[7]
Total	5,130.3	8,961.7

[1]Based on development existing in 1974 during a recurrence of the most severe drought period of record for each basin, respectively.

[2]One acre-foot = 325,851 gallons.

[3]Includes Texas share of Lake Texoma yield as provided under terms of the proposed Red River Compact. Total firm yield of Lake Texoma is estimated at 2,010.0 thousand acre-feet annually.

[4]Based on current water rights.

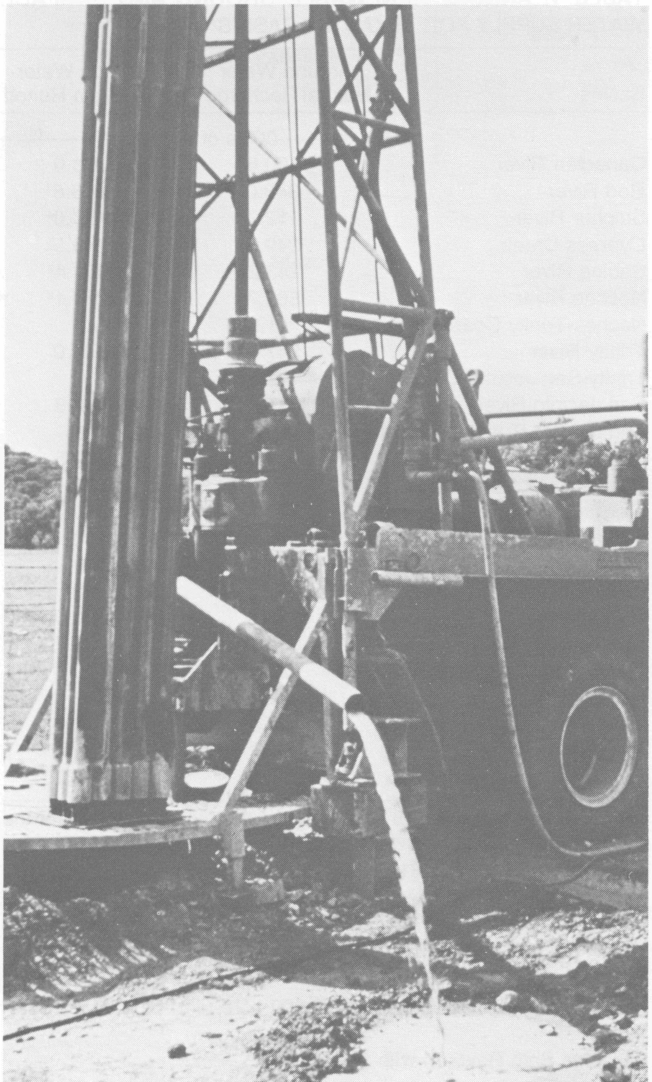
[5]Texas share of Toledo Bend (950,000 acre-feet) plus other reservoirs.

[6]Includes Sam Rayburn with power.

[7]Includes only Texas share of Amistad and Falcon.

Source: Texas Water Development Board, *Continuing Water Resource Planning and Development for Texas*, Draft Report, May 1977, and letter from Herbert W. Grubb, Director, Planning and Development, Texas Department of Water Resources, June 12, 1978.

Ground-Water Management


State agencies have no control over drilling of irrigation wells or quantities of water pumped for irrigation.

Present efforts to manage ground water in Texas are on a local basis for limited objectives. For practical purposes, ground water is that water extractable from the earth through wells. All usable ground water results from the infiltration of precipitated moisture through the soil mantle to the water table. From this point it moves through porous rocks in accordance with physical laws (3).

Section 52.001, Texas Water Code, defines ground water as: "Water percolating below the surface of the earth and that is suitable for agricultural, gardening, domestic or stock raising purposes but does not include defined subterranean streams or the underflow of rivers."

The major part of Texas ground water occurs in comparatively few aquifers. A major aquifer may be defined as one which yields large quantities of water in a comparatively large area of the State. Figure 2 shows the location of the major aquifers. With the exception of the Edwards limestone, the important water-bearing formations consist chiefly of sand, sandstone, or sand and gravel. And with the exception of the bolson deposits in West Texas and the Ogallala formation in the High Plains, they all contain water under artesian pressure in the areas of heavy withdrawals (3).

The leading Texas court decision on legal rights in ground water is *Houston & T. C. Ry, Co. v East,* 81 S.W. 279 (Tex. Sup. 1904). The Texas Supreme Court found applicable the English rule of absolute ownership and declared that "a person who owns the surface may dig therein and apply all that is there found to his own purposes."

Later cases confirm that under the law of the State of Texas, a landowner has the right to drill wells and appropriate all of the underground percolating waters without regard to the effect upon other landowners. This right is an interest in real estate and may be exercised by the landowner or sold to others for use off the land (3).

The general opposition to control of individual rights at any level, be it federal, state or local, effectively prevents the initiation of comprehensive management programs. Once an individual obtains well-recognized unregulated water rights of long standing, it is understandable that he will go to great lengths to protect these rights from abridgement. Few landowners would voluntarily cooperate in a ground-water control program. The effects of water depletion are slowly manifested, do not touch all users equally or simultaneously, and may delay concerted action until it is too late to provide an effective remedy (59).

The magnitude of recognized ground-water rights in Texas prevents extension of appropriation to ground water, as it was earlier applied to surface water. The divestment of such well-defined water rights probably would be considered an unconstitutional taking of property. Court decisions have welded the absolute ownership rule into a rule of property which would be most difficult to overturn when many rights are recognized in Texas (25).

The activities of State water agencies are limited to fact finding, data gathering, and analysis of the ground-water situation. The State agencies have no

Figure 2. Major aquifers of Texas.
Source: Texas Water Development Board.

control over drilling of irrigation wells or quantities of water pumped for irrigation (43).

In 1968, a National Water Commission was authorized by Congress. Their report (35) on a national water policy, published in 1973, emphasized three ground-water management problem areas: (1) integrating management of ground water and surface water, (2) mining of ground water, and (3) ground-water quality. The Commission concluded that "a uniform national ground water law is not desirable because of a great variety in: aquifer characteristics; legal regimens allocating the resources; and in the economic and social milieu in which it takes place." But the Commission concluded that lack of sufficient ground-water management represents a national problem (43).

Among specific recommendations made by the Commission concerning mining of ground water was that states should institute the regulation of ground-water withdrawal and that the regulation take into account the value of present use of ground water compared to future use for the purpose of establishing a rate of depletion. The primary concern of the Federal government in this matter is the long-term supply of food and a smooth transition from an irrigated economy to a dryland economy. At the Federal level of government, the Commission recommended that ground-water resources be included in future federal water resources planning and an evaluation of state regulation and management be included in planning agency reports. They also recommended that evaluation of federal rescue projects consider circumstances giving rise to the rescue projects including presence or absence of state and local ground-water regulation and management (43).

In the late 1940's the rapid lowering of the water table of the Ogallala ground-water formation because of irrigation pumpage created concern. Many believed that water was being wasted, that competition between closely-spaced wells was reducing their efficiency, and that the water was being mined because withdrawals greatly exceeded recharge. The High Plains Water Association was formed to push for remedial legislation. This culminated in 1949 with enactment of the State law authorizing creation of Underground Water Conservation Districts (3).

Active districts include the High Plains Underground Water Conservation District, headquartered at Lubbock; North Plains Ground Water Conservation District, Dumas; Panhandle Ground Water Conservation District No. 3, White Deer; Harris-Galveston Coastal Subsidence District, Waller; and Edwards Underground Water Conservation District, San Antonio. The latter two districts were created by the Legislature, which declined to give them the authority to prorate production of wells. The other districts have this power but have declined to use it. Most districts have directed their efforts toward prevention of waste, well spacing, well recharge, conservation education, and data gathering on water-table levels. They have not made any effort to regulate the production of water from wells directly (3).

Any area in Texas can be included in a district if it has substantial ground-water resources, if its boundaries can be determined within the terms set out by the law, and if its people vote to form a district. All of the area within an aquifer or a subdivision of an aquifer should be made a part of any ground-water district created therein. The choice of cities, counties, or precincts electing not to participate in a district tends to fragment the district and limit the effectiveness of ground-water conservation programs and the equity of their funding (37).

The Ogallala Aquifer

The Ogallala Aquifer supplies the High Plains of Texas with nearly all of its water for irrigation, municipal, and industrial uses. This area includes about 35,000 square miles in 42 counties. Roughly rectangular in shape, it averages 300 miles north and south and 120 miles east and west and is divided into two sections by the Canadian River. The land is level and clear, with uniform soils, and is particularly well suited to agriculture when sufficient water is available (50).

The High Plains accounts for two-thirds of the total irrigated acreage in Texas. The Ogallala Aquifer is a declining water supply of uneven distribution. In some areas, the saturated thickness of the aquifer is less than 50 feet; in other areas, it is more than 500 feet. Severe diminution of the water supply occurs in the thin sections. In some areas of the Southern High Plains, the water supply is essentially depleted, and irrigated cropland has been converted to dryland farming or is being returned to grasses (50).

The amount of ground water used on the High Plains in 1974 was estimated at 8 maf or 78 percent of the ground water used in the State in that year. New wells continue to be drilled to irrigate new acreages and to provide more water where older wells have declined in pumping rates. At projected rates of use, the present ground-water supplies in much of the Southern High Plains area are expected to be depleted to the point that they will not support irrigation by the year 2000, while those of the northern area may support widespread irrigation to 2040 and beyond. The declining water supplies of the High Plains region are among the most severe Texas water-supply problems (50).

Lateral movement may contribute somewhat to local water supplies in some aquifers. Generally, the total quantity of water that can be physically extracted in a given situation is dependent upon the thickness and permeability of underlying saturated materials. The amount of water that can be economically extracted depends upon the price that can be paid for recovery. Thus, physically and economically recoverable quantities of water are likely to differ considerably. The Ogallala formation is characterized by a stable water-supply area. According to Cronin, "Ground water moves at a rate of about 2 inches per day in the vicinity of Plainview in Hale County..... It is recognized that this estimate is valid only under the geological and hydrological conditions assumed; however, it is believed that the estimate is of the proper order of magnitude for the Ogallala formation throughout the Southern High Plains (14)."

This rate of movement is equivalent to about 61 feet per year, or 1 mile in 87 years. This slow rate of water movement and continued irrigation on adjacent farms tends to maintain existing hydraulic gradients. The result is that the total available water supply tends to be fixed for individual land owners (23).

Ground-water management was made the responsibility of local people with the passage of a local option ground-water control law in 1949 allowing the establishment of local ground-water management districts. Aside from the data gathering and educational pursuits, Texas districts have the authority to require well permits, space wells, prohibit waste, and limit the quantity of water pumped. They have exercised all of their authority except limiting the quantity of water pumped. Permits are required, tailwater pits to eliminate waste are encouraged but not mandatory, and spacing of wells is dependent upon casing size and well yield. There are no restrictions for farmers drilling irrigation wells outside of the operational ground-water management districts (43).

Other states underlain by the Ogallala Aquifer vary in their institutions for ownership and management. In Colorado, ground water is controlled by the state. In Kansas, all water is dedicated to the use of the people of the state, subject to the control and regulation of the state. Control of ground water in Nebraska is an unresolved legal issue. The state exercises no direct control other than to require spacing of 600 feet between irrigation wells and registration of wells. Ground water in New Mexico belongs to the public. Ground water in Oklahoma belongs to the landowner, but its use is subject to Oklahoma ground-water law. Ground water is controlled by the individual landowner in Texas (43).

In New Mexico and Oklahoma, an attempt is being made by state agencies to ensure reasonable use by irrigators. New Mexico administration prescribes that the irrigation allocation should not be consumed in a period of less than 40 years, dating from 1952 for Lea County and from 1956 for the Portales Valley. Oklahoma will allocate water to landowners in the various ground-water basins to ensure that adequate irrigation water will be available until at least 1993 (43).

Section 193 of the Water Resources Development Act of 1976 authorizes the Secretaries of Commerce and Army, with other appropriate federal, state and local agencies and the private sector to study the natural resources of the High Plains (Ogallala) Regions of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, and Texas. The stated purpose of the effort is to assure an adequate supply of food to the Nation and to promote the economic vitality of the High Plains Region. The act specifies that the agencies named shall study the depletion of natural resources of those regions of the states presently utilizing the declining water resources of the Ogallala Aquifer and develop plans to increase water supplies in the area. A final report, with recommendations, shall be transmitted to Congress no later than July 1, 1980 (50).

The Gulf Coast Aquifer

Ground-water development and use is one of the resource cornerstones supporting the remarkable growth and economic diversity of the Texas Coastal Zone. Water from wells, in addition to surface water, has supplied area needs since the middle of the last century. Since 1930, use of water by growing cities, expanding industries, and irrigation agriculture has increased rapidly (60).

Most of the coastal area has not lacked for water resource availability. All of Texas' major river systems discharge into the Gulf. Their sediment transport feeds its beaches; their waters maintain estuarine environments; and, where conditions are favorable, the rivers recharge Coastal Zone aquifers as they cross outcrop areas. Ground-water management issues in the Coastal Zone are related to the opportunities for improving the optimal mix of surface and ground water sources for this heavy water-using region (60).

The Gulf Coast Aquifer is a series of alternating clays, silts, sands, and gravels of the Catahoula, Oakville, Lagarto, Goliad, Willis, Lissie, and Beaumont formations. Ground-water-bearing aquifers are not consistently productive throughout the Coastal Zone. Water quality varies in the complex lenticular sand units, both vertically and horizontally (60).

The development and use of the Gulf Coast Aquifer has created some difficulties. Problems have included declining water levels, land surface subsidence, salt water intrusion, and water quality impairment from surface and subsurface disposal of wastes. Increasing costs of ground-water supply are not shared equitably by all of the ground-water users in the area. Records of long-term water quality monitoring by the U. S. Geological Survey, in cooperation with state agencies and the City of Houston, indicate changes in the slope of the ground-water surface. Heavy pumpage in the Houston area has caused an irregular alteration in the fresh-salt water interface in the ground-water bearing units. As the generally gulfward gradient has been reversed, salt water has been moving slowly inland toward areas of heavy development (60).

A total management strategy for all the surface and ground-water sources that supply the Coastal

Zone would be complex. Effective use of available resources might be enhanced by such a management program. Present Texas law relating to use of ground water leaves many questions unanswered and problems unsolved. Decisions by Texas in the area of ground-water management may be hastened by federal policies or actions. There is evidence of an increasing federal intent to impose federal controls and guidelines where necessary to prevent waste or quality impairment of the nation's ground-water resources (60).

A successful ground-water management program for the Gulf Coast Aquifer may require each water user to give up totally independent action in order to achieve a common benefit. Experience has shown that an individual user of a ground-water basin will not voluntarily exercise a management and conservation program unless he believes that his own resources are threatened. This attitude may affect broader interests adversely because negative effects on a ground-water basin do not touch all users equally at the same time. These effects are progressive. Before all users are equally affected and equally concerned, it may be too late to apply remedial measures (60).

The coastal area has had continuing analytical studies of its water needs and the potential sources for meeting these needs. There are choices to be made between mixes of surface and ground water supplies and among institutional and financial arrangements. Technical means are available to accomplish the goals of the coastal area. The declining water levels, irreversible land surface subsidence, and salt water encroachment already experienced indicate that the Gulf Coast Aquifer is an exhaustible resource. Choices must still be made as to the extent and purpose of future use and the appropriate federal, state, and local responsibilities (60).

The Harris-Galveston Coastal Subsidence District was created by special legislation in 1976 as a means of grappling with the serious land surface subsidence problem related to excessive ground-water withdrawal. The powers of the district are much broader than those of the other active special law district, the Edwards Underground Water District. The district takes in all of Harris and Galveston Counties. It is governed by a board which can develop a plan determining the areas subject to subsidence and make rules under which well permits will be issued. Existing wells receive an automatic permit, but permits for new wells are granted for periods of one year at a time. The district also is authorized to regulate spacing of wells and rates of pumpage (44).

The Edwards Aquifer

The Safe Drinking Water Act, Public Law 93-523 includes Section 1424(e) which requires that:

"(e) If the Administrator determines, on his own initiative or upon petition, that an area has an aquifer which is the sole or principal drinking water source for the area and which, if contaminated, would create a significant hazard to public health, he shall publish notice of that determination in the Federal Register. After the publication of any such notice, no commitment for Federal financial assistance (through a grant, contract, loan guarantee, or otherwise) may be entered into for any project which the Administrator determines may contaminate such aquifer through a recharge zone so as to create a significant hazard to public health, but a commitment for Federal financial assistance may, if authorized under another provision of law, be entered into to plan or design the project to assure that it will not so contaminate the aquifer." (16)

In 1975, the Administrator of the Environmental Protection Agency was petitioned to designate the Edwards Aquifer as a sole source aquifer under the provisions of the Act. A study was made of the geologic setting. The Edwards Plateau is a southeastern extension of the High Plains of West Texas. In contrast to the High Plains, where elevations range from about 2,500 to 4,000 feet above sea level and where the land surface is flat to moderately undulating with scattered depressions and lakes, the Edwards Plateau is generally less than 2,500 feet, is deeply eroded and rapidly drained, and is a level upland only in its central portion (16).

The Edwards Underground Reservoir includes by far the most important water-bearing rock units in the San Antonio area in terms of total capacity and total water withdrawals for municipal, industrial, and agricultural supply. This aquifer is the source of the largest fresh-water springs in Texas (16).

Although about 10 percent of the recharge of the Edwards Underground Reservoir is the result of direct infiltration from precipitation on the aquifer outcrop in the Balcones Fault Zone, about 90 percent is primarily from seepage from streams. Aquifer recharge is closely related to streamflow. All streams, except the Guadalupe River, that flow in from the Edwards Plateau lose most of their flow to the aquifer as they cross those areas where the aquifer crops out or is near the land surface in the Balcones Fault Zone (16).

The Edwards Underground Water District is the principal State-chartered coordinating agency for ground-water development and water-quality monitoring in the five-county Edwards area. The District, organized in 1959, was designated by the Texas Water Quality Board as the regional agency to coordinate and supervise the administration of the TWQB order for the Edwards Underground Reservoir. The Edwards Underground Water District's monitoring network includes observation wells on all parts of the area (16).

The Environmental Protection Agency designated the Edwards Underground Reservoir as a sole source aquifer in the San Antonio area effective November 15, 1977. Regulations were put into effect under the aquifer requirements of the Safe Drinking Water Act. The regulations establish procedures for reviewing commitments of Federal financial assistance to projects in the San Antonio area. Once an area is designated, no subsequent commitments of Federal financial assistance may be made to projects which the administrator of EPA determines may contaminate the aquifer so as to create a significant hazard to public health. The review process is delegated to the Regional Administrator except for the final determination of health hazard (16).

Other Aquifers

Ground water is a major source of fresh water for municipalities, industries, and agriculture throughout Texas. As the population has grown, the withdrawal and use of ground water have increased. Aquifers in addition to the Ogallala, Gulf, and Edwards are being seriously depleted of fresh water and are expected to suffer water-quality deterioration (50).

Hueco Bolson Deposits

The City of El Paso is the largest water user in El Paso County. The major source of the city's water supply is the Hueco Bolson Deposits. The City of Juarez just across the Rio Grande from El Paso in Mexico is the second largest user of ground water for municipal and industrial purposes in the El Paso area. Its source of ground water is also the Hueco Bolson Deposits (50).

Ground water from the Hueco Bolson Deposits is being mined. Depletions in storage are causing saline-water encroachment and degradation of ground-water quality. The natural recharge of ground water in the Hueco Bolson Deposits in the El Paso area is considerably less than the discharge by wells. Presently, annual well discharge is 10 times the estimated average annual recharge to the aquifer, and water levels are declining approximately 2 to 3 feet per year (50).

Carrizo Aquifer

The Winter Garden District of South Texas includes all or parts of Dimmit, Frio, Maverick, Medina, Uvalde, and Zavala Counties. Throughout most of the district, the Carrizo Aquifer yields good quality water. During the 1960's, the average annual withdrawal by large capacity wells was approximately four times the natural recharge to the aquifer. In the heavily pumped irrigation areas in Zavala and Dimmit Counties, water levels have declined more than 400 feet (50).

Mining of artesian storage is causing leakage and encroachment of poorer quality water into the Carrizo Aquifer. In local areas, saline water from the Bigford Formation is leaking through old well bores and mixes with Carrizo water, degrading its quality. In the eastern outcrop area of the aquifer in Frio, Atascosa, Bexar, and Wilson Counties shallow ground water in the aquifer contains excessive natural concentrations of iron. Throughout its entire extent in the Winter Garden area south and southwest of San Antonio, the aquifer contains water which is very hard (50).

Trinity Group Aquifer

The Trinity Group Aquifer extends over a large area of North and Central Texas. Yields of large capacity wells in the aquifer range up to several thousand gallons per minute (gpm). In thinner sections of the aquifer where it supplies water principally for domestic use, most wells yield less than 100 gpm (50).

The sustained heavy pumpage in the Dallas-Fort Worth area for municipal and industrial purposes has caused a significant reduction in water levels. At the present time, water levels in the Dallas-Fort Worth area range from 400 to 1000 feet below land surface. As the use of ground water continues from the Trinity Group Aquifer, water levels will continue to decline, since withdrawal exceeds recharge. Water quality declines and pumping costs increase as the water levels in the aquifer are lowered. This threatens the water supplies of some of the cities in the north-central Texas area.

Areas of Concern

Guyton (19) listed the following areas as having potentially serious underground water problems:

1. The Houston metropolitan area, including most of Harris County and parts of Waller, Fort Bend, Brazoria, Galveston, Chambers, and Liberty Counties;
2. All of the High Plains area;
3. The Dallas-Fort Worth metropolitan area, extending northward through Sherman;
4. The Orange metropolitan area;
5. The Edwards Limestone Reservoir area, including parts of Kinney, Uvalde, Medina, Bexar, Comal, and Hays Counties;
6. The Winter Garden area, including at least La Salle, Dimmit, Zavala, and Frio Counties;
7. The Lufkin-Nacogdoches area;
8. Parts of the coastal counties between Houston and Victoria;
9. Parts of Pecos and Reeves Counties;
10. Parts of the El Paso metropolitan area;
11. Some other, less-publicized areas where ground-water developments have been made and where problems of one kind or another have been encountered, such as Reagan and Glasscock Counties, Haskell and Knox Counties, the Van Horn area, the Dell City area, the Henderson area, the Kilgore area, the Tyler area, the Stephenville area, and the Kerrville area.

In Texas, all standing water of more than 5,000 acre-feet is in manmade reservoirs built since 1930.

Surface-Water Management

The two basic doctrines of surface-water rights recognized in Texas are the riparian doctrine and the appropriation doctrine. The corresponding water rights perfected under these doctrines are commonly referred to as riparian rights and appropriative rights. The riparian right is a common law right to use a proportionate part of the normal flow of a stream as a part of the ownership of lands abutting the stream. The appropriative right is an acquired right under a procedure provided by statute to divert from a water supply a specific quantity of public water under a permit (52). Application for a permit is made to the Texas Water Commission of the Texas Department of Water Resources.

Surface water may be classified as diffused surface water or as water within a defined watercourse. Diffused surface water originates as rain, snow, or sleet and continues to be surface water until it reaches some natural channel or watercourse. Once it reaches a watercourse, it becomes part of the stream and is the property of the State, subject to the rights of owners of riparian lands and those who have obtained appropriation rights (52).

"The legal distinction between ordinary flow, underflow, and storm and flood flow is particularly significant in reconciling conflicting claims to the same water supply, which arise because of the dual recognition in Texas of both riparian and appropriation doctrines. The riparian right concept relates to and is concerned only with the ordinary flow and underflow of a stream. A riparian right does not attach to that portion of a stream comprised of storm and flood flow, and therefore generally will not attach to waters impounded by larger reservoirs." (52).

The appropriation doctrine was adopted by the State near the turn of the century. Since the Appropriation Act of 1895, land acquired from the State no longer carries riparian rights, and a statutory procedure has existed whereby individuals can obtain water rights from the State. All appropriation statutes expressly recognized the superior position of riparian water rights. At first, appropriation was accomplished through an informal procedure; the landowner simply filed a sworn statement with his county clerk describing his water diversion. Under such a loosely administered appropriation system, claims sometimes overlapped, described huge acreages to be irrigated, or claimed more water than the dependable flow of the stream could produce. Later, certified copies of these claims were recognized by the State, and thus they came to be called "certified filings." (2)

Since 1913, a more strictly administered procedure involves making application to a State agency, now the Texas Department of Water Resources, for a permit to appropriate water from streams. The several purposes for which water may be appropriated are identified in Sect. 5.023, Texas Water Code, and the order of priority or preferences between these uses is listed in Sect. 5.024, Texas Water Code.

At the end of December 1976, the Water Development Board reported authorized and claimed amounts of 56.9 maf of water (Table 2). Most existing permits claim water for irrigation, although many of the largest are for municipal and industrial use or for hydroelectric power generation. Permit holders must file annual reports of water use with the Water Rights Commission, so that reasonably accurate records of appropriative water use are available to aid water resource administrators and planners (44).

With both doctrines recognized in Texas, numerous riparian and appropriative rights exist on the same streams, creating problems for Texas courts and water agencies in trying to correlate these conflicting types of rights. Following years of unsuccessful attempts to correlate these rights, and to more accurately define and delimit the nebulous riparian rights, a Water Rights Adjudication Act was passed (Sect. 5.301-5-341, Texas Water Code) in 1967, and adjudication of water rights is currently in progress (44).

The actual process of water-rights adjudication started shortly after most of the unrecorded claims were received by the Commission. Once adjudication is completed, certificates of adjudicated water rights will be issued to successful claimants. If the Act survives expected court tests, then for the first time, riparian rights will be limited to a specific maximum quantity of water (44).

The Commission is attempting to cancel, either wholly or partially, unused appropriation permits. Some permits were obtained under the loosely ad-

TABLE 2. AUTHORIZED OR CLAIMED AMOUNT OF SURFACE WATER BY TYPE OF USE, BY BASIN, DECEMBER 31, 1976

Basin	Municipal	Industrial	Irrigation	Mining	Hydroelectric	Recreation	Total
	Acre-feet						
Canadian River	110,460	51,300	8,360	0	0	13,243	183,363
Red River	679,388	134,489	1,560,970	7,116	8,060	51,573	2,441,596
Sulphur River	181,618	167,097	2,175	0	0	6,514	357,404
Cypress Creek	107,092	255,874	7,070	762	0	7,259	378,057
Sabine River	501,112	1,284,912	153,905	751	0	62,795	2,003,375
Neches River	478,160	1,886,175	217,754	60	0	29,412	2,611,561
Neches-Trinity Coastal	0	2,621,849	176,464	120	0	55,400	2,853,833
Trinity River	2,543,519	2,083,757	571,428	23,587	50,319	1,830	5,274,440
Trinity-San Jacinto Coastal	0	30,000	24,854	0	0	622	55,476
San Jacinto River	231,000	718,405	19,273	5,554	0	7,060	981,292
San Jacinto-Brazos Coastal	12,000	4,388,828	84,031	0	0	1,880	4,486,739
Brazos River	644,733	2,045,432	839,103	46,992	1,500,000	46,210	5,122,470
Brazos-Colorado Coastal	0	32,000	25,248	23,000	0	0	80,248
Colorado River	296,757	538,296	1,363,088	18,815	6,790,700	11,355	9,019,011
Colorado-Lavaca Coastal	0	905,099	12,008	0	0	315	917,422
Lavaca River	24,990	80,010	4,645	0	0	455	120,131
Lavaca-Guadalupe Coastal	0	0	309	0	0	0	309
Guadalupe River	72,315	1,055,903	113,737	470	9,338,472	6,819	10,587,716
San Antonio River	1,472	48,903	107,427	335	75,000	4,659	238,757[1]
San Antonio-Nueces Coastal	240	0	106	0	0	52,650	52,996
Nueces River	290,695	258,930	354,976	20,000	20,520	30,777	975,898
Nueces-Rio Grande Coastal	10,370	2,018,419	129,314	0	0	43,477	2,201,580
Rio Grande River	184,541	105,600	3,795,931	7,875	1,882,500	21,526	5,997,973
Total	6,370,462	20,711,278	9,572,176	155,437	19,665,571	455,831	56,930,755

[1]Includes "Recharge" — 961 acre-feet.

Source: Texas Water Development Board, *Continuing Water Resource Planning and Development For Texas*, Draft Report, May 1977.

ministered certified filing system. Others represent unusual allocations of water made by permit from the Commission and its predecessors. Vested water rights such as these cannot be altered without a forfeiture proceeding, and the water to which they pertain is not subject to reappropriation until the permits are cancelled or reduced (47).

Progress to the judicial phase of adjudication and subsequent appeals probably will take many years. By September 1974, the Commission considered that the process of adjudication was about one-third complete (53) and expects adjudication to be completed in the next 10 years. In any event, it will be some time before all Texas surface-water rights are reasonably well established (44).

Diffused Surface Water

When water falls from the atmosphere as precipitation, it becomes diffused surface water. Diffused surface water is surface drainage over the face of a tract of land which is not yet concentrated into a channel or watercourse. An essential characteristic is that flows of diffused surface water are relatively short-lived.

In Texas, it is generally established that landowners have the right to intercept and use diffused surface water on their land. Their right is superior to that of adjacent lower landowners and to any suface-water right holder on streams into which the runoff water might eventually flow (5). The rule in Texas is similar to that in most other jurisdictions. No state has gone so far as to attempt appropriation of diffused surface water (5).

A Texas statute, Sect. 5.140 of the Texas Water Code, provides that diffused surface water can be impounded by the landowner on his own property without the necessity of obtaining a permit so long as the reservoir does not exceed 200 acre-feet in capacity. This includes the small impoundments commonly called stock tanks or farm ponds. Since 1953, water in these small reservoirs may be used only for domestic and livestock purposes. A permit is required from the State if the dam is on a stream course, if the reservoir exceeds the storage limits, or if the water is to be put to other uses. A recent Water Rights Commission survey of reservoirs exceeding 50 acre-feet storage capacity revealed more than 800 reservoirs which may require permits (53).

Downstream water users usually are of the opinion that small reservoirs and related conservation land treatment practices have the effect of reducing their water supply (4). A recent study of diffused surface water use in Texas by the Texas Society of Professional Engineers (48) gives a great deal of credence to this concern and concludes that such small impoundments result in major water losses.

The impact of such small reservoirs is determined by their size and number and the amount of runoff. The law permitting landowners to construct such reservoirs applies throughout the State and does not consider the wide variations in rainfall, runoff, and other hydrologic factors that affect surface water yield.

Small reservoirs are most numerous in the central part of the State where annual runoff, except for South Texas, exceeds one inch. For example, more than 8,000 stock tanks and farm ponds are in the Nueces River Basin's 19 counties according to a recent survey by the Soil Conservation Service. Because they can be constructed at will by landowners, the number is growing rapidly. Such reservoirs have an average capacity of only 6.5 acre-feet, but they intercept the runoff from a watershed averaging 136 acres (45).

It has been calculated that near El Paso a watershed of 24,000 acres is required, under normal conditions, to supply a 200 acre-foot reservoir, permitted under Sect. 5.140, Texas Water Code; 10,000 acres on the High Plains; 2,400 acres in Central Texas; and only 600 acres in East Texas (48).

Many small impoundments are quite shallow with large surface areas compared with storage capacity. Losses of water are heavy from evaporation, transpiration by vegetation, seepage, and percolation. In others, the quantity of water allowed to be impounded under Sect. 5.140 is large. A landowner without a permit can impound more than 65 million gallons of water in a single reservoir for domestic and livestock purposes, and he can build as many reservoirs as his land will fill. This is estimated to be 85 times the amount of water actually needed by a typical single-family cattle-ranching operation on three sections of land (48).

The fears of downstream water users that their water rights could be seriously impaired as small reservoirs in the watershed increase in number and size seem justified. Under present Texas law, they would have no legal recourse. The Texas Society of Professional Engineers has recommended that Sect. 5.140 of the Texas Water Code be revised and that no small reservoir larger than 10 acre-feet in storage capacity be allowed without a permit from the Water Rights Commission (48).

Water Within a Watercourse

A watercourse has been defined in Texas as having a bed, bank, water current, and permanent supply source. The stream need not be perennial but must flow regularly enough that a running stream is maintained for a considerable time. Water is obtained from two main sources — surface watercourses and ground water. The amount of surface water available is determined by the magnitude and distribution of the annual precipitation, the proportion of the precipitation that reaches the watercourses, and the availability of reservoir storage. Reservoir storage allows the changing of water allocation over time. Excess water during wet periods can be held and then released for use in dry periods. This reallocation may occur within a given year or over a period of several years. The water in storage is subject to losses due to evaporation and percolation into the underlying ground strata. Reservoir projects are usually located so that percolation losses are minimized, leaving evaporation losses as the major restriction on the quantity of water that can be made available for use through storage. The length of time water would have to be held in storage to even out the annual flows is determined by the variability in annual precipitation and runoff. The combination of the storage time required and the evaporation losses places an upper limit on the quantity of water that can be made available. If there were no storage losses, the mean annual runoff would represent the maximum quantity of water that could be made available for use over time (10).

Since losses do occur while water is in storage, the upper limit on water availability through storage will always be less than the mean annual runoff. The amount of the potential loss is a function of the annual evaporation losses and the length of time the water is held in storage. The storage time is directly related to the variability in annual precipitation. As the variability in precipitation increases, the storage time required to yield a uniform flow also increases (10).

After the abolition of the National Resources Planning Board in 1943 and the similar disposal of most state planning agencies, the states pursued their separate ways in water development, depending on their state finances and their political convictions. In Texas, until 1957, when the Texas Water Planning Act created a Planning Division in the Texas Board of Water Engineers, no single agency existed with authority for statewide planning (38).

In the case of water resource development, it is particularly necessary to plan well in advance, choosing carefully between alternative proposals, if the inclusion of one purpose excludes the possibility of creating another. The President's Water Resources Policy Commission of 1950 states that:

"Once they are completed, major water control features can be altered only with difficulty or not at all. There are only a relatively few possible dam sites, and once they are appropriated, the possibilities for economic multiple-purpose development are very limited. Once an irrigation project is developed, it cannot be moved because unfavorable soil or climate factors are discovered. There is a sobering finality in the construction of a river basin development; and it behooves us to be sure that we are right before we go ahead." (38)

In considering new water resource development and the benefit to be derived, it is useful to consider past experience in Texas. Canyon Dam is on the Guadalupe River in Comal County, Texas. It impounds a reservoir known as Canyon Lake, which has a surface area of about 8,300 acres. It is 9 miles long and 4 miles across at its widest point. The dam was built by the U. S. Army Corps of Engineers in 1958-64 for the purposes of flood control and conservation storage (12).

Canyon Lake is the only large impoundment in the Guadalupe River Basin. Because it is isolated from the effects of similar projects, it was selected in 1974 for a reservoir-impact or hindsight study. The purpose of the research was to compare expectations and results from the project. Expectations were determined from the records of meetings, hearings, communications, and legislation over the 30 or more years between the first mention of a large dam on the Guadalupe above New Braunfels and the beginning of construction. Dr. Earl Cook of Texas A&M University, the Principal Investigator for the study, made this summary of the changing mix of anticipated benefits.

"In the three decades between the earliest proposals for a large dam on the upper reaches of the Guadalupe River and the start of construction on Canyon Dam, the mix of anticipated benefits changed considerably.

"Benefits to navigation loomed large in the early vision, but were regarded as negligible in the final analysis; the generation of electricity was a major aim for 25 years and was retained in the final plans as a future alternative; after the completion of the small hydroelectric plants downstream, the benefits of controlled release to them became apparent. The perception of future benefits from conservation storage seems to have grown mainly during the prolonged drought which ended in 1957, for until then the basin's needs for municipal, industrial, and irrigation water had been taken care of adequately by ground water and existing surface supplies, including the springs along the Balcones Escarpment. The anticipation of large benefits from water-related recreation was late-blooming. The only benefit whose anticipation was carried undiminished through these thirty years was that of flood control; floods during this period served to accentuate the perception and augment the calculation of benefits to be obtained from flood control.

"A benefit confidently anticipated by almost everyone involved in the planning and promotion of Canyon Reservoir was a general lift to the economy of the basin. The anticipation of such external benefits lay behind the reluctance to abandon power production as a purpose, as it lay behind the early emphasis on navigation improvement and the later emphasis on water conservation. The expectation that cheap freight rates, cheap electric power, a guaranteed water supply and flood protection would attract industry was linked to the assumption that industrialization would bring pervasive economic benefits to the Guadalupe basin." (12)

One of the aims of a hindsight study is to determine whether a project has been a good investment of public funds. In the case of Canyon Reservoir, the evaluation team concluded that flood crests were actually reduced. The major economic benefit was the transfer of federal funds into the region to build the dam and operate the reservoir. Ecological costs were minor. The chief beneficiaries were the owners of land in the floodplain below the dam, the owners of land around the shoreline of the reservoir, and the recreationists who use the lake. The cost is being borne mainly by all taxpayers and partially by the sale of water. Under existing law, the water in the reservoir constitutes a reserve, probably for municipal use (12).

Reservoirs

Section 5.028 of the Texas Water Code, known as the Wagstaff Act, was enacted in 1931. It reads as follows:

"Any appropriation made after May 17, 1931, for any purpose other than domestic or municipal use, is subject to the right of any city or town to make further appropriations of the water for domestic or municipal use without paying for the water. However, this section does not apply to any stream which constitutes or defines the international boundary between the United States of America and the Republic of Mexico." (39)

Although the statute has been in effect for many years, its authority has not been exercised by any city or town to date. Therefore, there is only limited interpretation by the courts as to the constitutionality of this statute (39).

In a water-short area, a large reservoir can fully develop the water resources of the watershed upstream from the reservoir. A necessary part of this development is a permit from the Water Commission appropriating to the user the right to use the water developed. For a large project, this can result in there being no more water available for appropriation in the watershed upstream from the reservoir. The Commission is statutorily prohibited from granting a permit if it finds there is no water available for appropriation or that it would impair existing water rights. This inability to grant permanent rights to use water applies even if a prior municipal or industrial water right may not be fully utilized for many years in the future (39).

The Commission may alleviate this problem by the issuance of water permits for a specific number of years until it is needed by the downstream user. Thus far, these term permits have been restricted to uses that are compatible with a limited period such as irrigation and some industrial uses (39).

The surface-water resources available for use on an annual basis were summarized by the Texas Water Development Board from a variety of sources. Direct runoff of rainfall and spring flow from underground formations comprise the largest source of fresh water in the rivers and streams of Texas. The highly variable nature of rainfall and its associated runoff have required the construction of reservoirs which alter the natural distribution of streamflow and augment surface-water supplies (50).

To assess the total available surface-water supply, the Board used two basic hydrological techniques. The results of the Board's Hydrologic Data Refinement Study were used for those basins for which it had been completed (Sabine, Sulphur, San Antonio, and Guadalupe River Basins); while the naturalized flows computed in the Bureau of Reclamation Texas Basins Study were updated for the remaining basins. The procedure involves a simple arithmetic accounting of all gains and losses in each reach of the river basin being analyzed. Surface water available from runoff in 1974 is summarized by basin in Table 1 (50).

The storage capacity is the volume of water that can be held within the reservoir. The capacity of each reservoir is divided into four categories: dead storage, conservation storage, flood-control storage, and total storage capacities. The dead storage capacity is the volume below the lowest outlet level of the dam from which water cannot be released by gravity flow. The conservation storage capacity is the volume between the lowest outlet and the normal maximum operating level from which water can be released or withdrawn for beneficial uses. The flood control storage capacity is the volume below the lowest uncontrolled spillway crest or top of gates of a dam allocated to store floodwaters, which can be released at a controlled rate as rapidly as channel capacities permit without causing damage downstream. The total storage capacity is the maximum volume provided by the lowest uncontrolled feature of the reservoir dam, which may be the emergency spillway crest, the service spillway crest, the invert of inlet to the outlet works, top of gates, or top of dam below which storage can be controlled and above which uncontrolled spillage occurs (29).

The firm yield for a reservoir can be expressed as the maximum amount of water that can be supplied continuously by a reservoir under conditions of the driest and most severe drought period known to have occurred at that site. The firm yield will be larger than the dependable or safe yield that assumes a safety factor. The contribution of a reservoir to a system supplying a specific water requirement is dependent upon the content in conservation storage at the beginning of the critical period and the amount of inflow to and losses from the reservoir during the period. Firm yield is decreased by net loss of water by evaporation from the reservoir surface, by leakage, by seepage or infiltration, and by evapotranspiration from adjacent ground and vegetation (29).

The firm yield and the dependable yield of a reservoir will be reduced each year the reservoir is in operation as the initial conservation storage capacity is depleted by sedimentation. Sediments consisting of silt, clay, sand, rock and other materials are transported in suspension and by movement along streambeds by water flowing into reservoirs. As the capacity of a reservoir is reduced by sedimentation, less water can be held in conservation storage. The locations of the sediments deposited in the reservoir alter the area-capacity relationships and may have a significant effect upon reservoir yields (29).

Conservation storage capacities and contents yield differently in different parts of Texas. In humid East Texas, a reservoir may provide a firm yield equal to or larger than its conservation storage capacity. In subhumid Central Texas, a reservoir may provide a firm yield equal to only one-fifth or less of its conservation storage capacity. In semiarid and arid West Texas, a reservoir may provide a firm yield varying within a range equal to one-tenth to one-thirtieth or less of its conservation storage capacity. Compilations of reservoir capacities and contents are only relatively indicative of the available water supply. Detailed studies are necessary to provide reliable estimates of the true water supply potential (29).

In some cases, the capacity of a conservation storage reservoir has been determined on the basis of design drought criteria and an existing need for water for a particular purpose. In other cases, the capacity is determined on the basis of design-drought criteria and future water requirements. When the needed capacity has been determined, hypothetical reservoir operations are planned using the design drought criteria applicable to the area. This determines the size of reservoir sufficient to supply the water requirement (29).

For any group of independent water supply systems, the level of water deficiency that creates supply problems will be different for each system. Each faces a different level of demand determined by prices, consumer composition and the like. Each has a different safe yield determined by capacity and management decisions. Therefore, the level of natural variation in rainfall at which each system will be unable to meet demand will be different. Weather constituting a drought for one system may cause no problem in meeting demands for water by other systems. Relatively common periods of rainfall shortage may be enough to bring some systems to the point at which restrictions will be instituted or emergency supplies tapped (6).

Average annual demand may be a fairly stable figure which can be estimated in advance from expected population growth and projections of per capita water use based on knowledge of social habits that change relatively slowly. But the naturally available annual supply will be highly variable. It will depend on climatic and hydrologic conditions in the region as total precipitation is modified by ground water and runoff conditions to produce variations in streamflows. Supply adjustments may include reservoir storage, aimed essentially at leveling supply (6).

Water supply systems are complex networks designed to collect, store and distribute water. The system planning process considers the functions of collection and storage, since these are most important to an understanding of the impact of long-term water storage. Water system planners seek out and evaluate available sources of supply in response to actual and anticipated levels of demand. There is almost always a choice of size and timing of development, and frequently of source as well. Costs of expansion are compared with possible costs of shortages to be expected if expansion is postponed. Demand tends to increase directly with a growing urban population and increases in per capita water use. Since both reservoirs and wells provide new water supplies in relatively large amounts at one time, the characteristic pattern of system growth involves the periodic introduction of oversupply. This surplus is eliminated if demand continues to grow. In event of drought, a system which has recently completed a large addition to its capacity has less of a water supply problem than a system which has allowed demand growth to approach or exceed available supply (6).

The basic supply capacity of a water system is determined by its flow and storage characteristics. Water inflow varies with rainfall, streamflow, runoff and recharge. Storage is much less varied and is reported in relation to capacity of available reservoirs. Storage changes the level of flow which can be attained on a stream over a period of time. It is difficult to be sure of the amount of storage needed to produce a given flow at a particular level of assurance such as 95 percent. One method of estimating storage requirements on a stream is by a "design drought" or some specific period of low flows. Reservoirs are then designed to provide the required flow even under the precipitation-runoff condition existing during the "design drought." The required flow can then be considered a "safe" yield in the same sense of probability of occurrence (6).

Aging of Reservoirs

Geologic creation did not provide Texas with any large, natural bodies of water. All standing water of more than 5,000 acre-feet in the State is in manmade reservoirs built since 1930. Many of these reservoirs are already showing signs of aging. Careful management is required for reservoirs and for entire river basins if aging is to be kept under control. Mrs. Lou Ellen Ruesink, Editor of *Texas Water Resources*, has described the aging process as follows:

"All lakes age naturally by filling up with sediment and decomposed organic matter; however, many natural lakes formed thousands of years ago are younger in lake age than modern Texas reservoirs.

"When a reservoir is no longer able to serve its intended functions — water conservation, power plant cooling, flood control, recreation, or municipal supply — it is considered functionally extinct. It is also extinct when the cost of maintenance is more than the benefits derived from it.

"An extinct lake may fill up with silt and organic material so that it is no longer able to hold water for flood control or conservation just as a reservoir designed for power plant cooling will not be functional when filter-clogging algae or plants become too big a problem. Environments unsuitable for good fish to survive or water unpleasant to look at or drink are other signs of extinction.

"Many lakes within the state will become extinct long before they should unless management practices are developed to slow down the rate of plant production.

"Reservoir planners estimate the useful lifespan of a reservoir before construction ever begins. Nutrients, light, temperature, and watershed sediment load are all considered in determining the number of years of expected usefulness. Lifespan for Texas reservoirs is considered to be only 100-125 years.

"The major sign of advanced age in Texas reservoirs is excessive algae and weed growth encouraged by an oversupply of nutrients, shallow lake basins, long hours of sunlight, and mild winter temperatures. Agencies such as the

Soil Conservation Service have educated farmers, highway builders, and developers to minimize sediment load in runoff. The siltation problem (reservoir filling up with sediment from fields upstream) is no longer as major as it once was." (41)

Eutrophication is the natural aging of a lake or of a reservoir which is a manmade lake. All reservoirs are aging and will eventually die. Lifespan and usefulness of reservoirs can be lengthened and enhanced by proper care.

There are two basic types of reservoirs in Texas: soft water, protected reservoirs of East Texas, and hard water, wind-whipped reservoirs of Central and West Texas. East Texas reservoirs, protected by hills and trees, are quite clear and stable and are typical of reservoirs found throughout the Southern Pine Forest states (41).

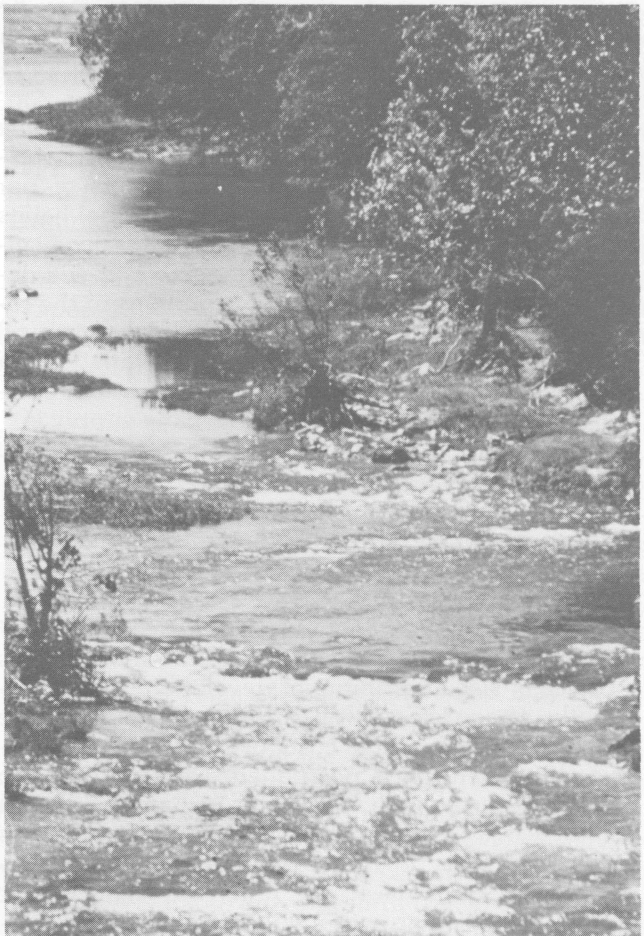
Central and West Texas reservoirs, and those found throughout the Central and Southwestern United States, are generally shallower than those in East Texas and have almost constant suspended turbidity. Water in these reservoirs may be as much as ten times as hard with twice as much phosphorus and other nutrients as those lakes in forested areas. The chemical nature of the lakes is very different because of the types of runoff areas: forest land in East Texas, limestone and agricultural land in Central and West Texas (41).

Such rooted water weeds as water hyacinth and hydrilla choke entire areas of East Texas reservoirs. Rooted plants are not a problem in Central and West Texas reservoirs because of the wind and turbidity. Over production in these reservoirs is in the form of a floating microscopic algae. Management practices to slow plant production include reduction of new nutrients coming into a reservoir and removal of nutrients already there (41).

Sewage effluent is a principal source of nutrients. Almost all of the treated sewage in Texas is heavily loaded with phosphorus and nitrogen because tertiary treatment to remove them is not required. Another major source of nutrients in reservoirs is agricultural runoff. The same nutrients a farmer adds to his fields, when washed into a reservoir, will certainly stimulate plant production (41).

Flushing at certain times of the year when the water in a reservoir is loaded with nutrients is desirable if the practice is compatible with reservoir management for flood control or conservation. The first heavy rain in the spring is loaded with nutrients and could be flushed immediately. Later runoff is relatively clean (41).

Surface water in reservoirs does not have as many nutrients as lower layers because the nutrients have been taken up by plants. When the plants die, they sink to the bottom and release nutrients into that layer. Plant harvesting is a way to remove existing nutrients from a reservoir. Experiments are under way using large floating harvesters to cut and bale water weeds to be used for cattle feed (41).


Sufficient inflow of fresh water is necessary for the protection and maintenance of Texas estuaries.

Fresh-Water Inflows for Estuaries

The Texas Gulf Coast has ten estuarine systems scattered from Louisiana to Mexico. These are Sabine-Neches, Trinity-Galveston, Brazos, East Matagorda, Colorado, Lavaca-Tres Palacios, Guadalupe, Mission-Aransas, Nueces, and Laguna Madre (Figure 3). They vary considerably in size, volume, use, accessibility, commercial importance, and ecological characteristics (28).

Texas Senate Concurrent Resolution 101 sponsored by Senator A. R. Schwartz of Galveston in 1974 recognized that a "sufficient inflow of fresh water is necessary to protect and maintain the ecological health of Texas estuaries" and that "the Texas Council on Marine-Related Affairs, in cooperation with other interested and knowledgeable parties, undertake a comprehensive study of the problem of providing estuarine inflows." The resolution resulted in a study by the Center for Research in Water Resources at The University of Texas at Austin.

The study area chosen was the Corpus Christi Bay System and part of the Coastal Bend Council of Governments. Three primary reasons for the choice were (1) the area contained an active harbor, a metropolitan center, a controlled watershed, a commercial fishery, and other typical developed components; (2) the data on the surface-water resources of the area appeared sufficient for illustrative mathematical modeling; and (3) the area was already the subject of intensive study aimed at developing analytical tools for coastal zone management (28).

Estuaries are semi-enclosed coastal bodies of water which have a free connection with the open sea and within which sea water is diluted with fresh water from land drainage. Sea water from the Gulf of Mexico has a characteristic salinity of about thirty five parts per thousand. Low-salinity fresh water dilutes the high-salinity sea water and produces a salinity pattern which ranges below that of the Gulf. Estuaries along the Texas Gulf Coast are characteristically of the shallow, drowned river type, show almost complete vertical mixing, and have relatively high net biological productivities (28).

Normally, sea water enters the estuary during high tide, and a mixture of marine and fresh water leaves during low tide. Shallow, circular estuaries, such as most of the Texas Gulf systems, can have much of their water blown out to sea during "northers" and can have smaller sections left dry during lesser storms. Internal obstacles have a critical impact on circulation patterns in some estuaries. Oyster reefs, transportation causeways, spoil islands, and solid waste dumps may hinder and redirect water flow (28).

Human use of estuaries includes such activities as industrial water supply (particularly cooling), transportation, commercial fishing, waste disposal, recreation and mineral extraction. Nature uses estuaries and surrounding areas as aquatic nurseries and wildlife and fish habitats. Estuaries play a vital role in the life cycle of an estimated 65 percent of the nation's marine fisheries. Human modification of fresh-water inflow commonly impairs biological functions of an estuary (28).

A relatively low species diversity derives directly from the high-stress conditions found within estuaries. Wave action, tidal cycles, storms, and variable currents affect estuaries, precluding development of stable climax ecosystems. Organisms selectively adapted to this environment normally have one or more defensive mechanisms for escaping or weathering short duration environmental extremes. Long duration problems cause large-scale changes in species structure. Some Texas estuaries have lost long-established oyster colonies because decreased river flows for several consecutive years caused estuarine salinity concentrations to rise to levels preferred by oyster predators (28).

Organisms now comprising estuarine communities have been adapting structurally and behaviorally to their environment since long before the settlement of Texas, and herein lies the sensitivity of estuaries to industrial man. Biological evolution cannot keep pace. Species are replaced by others already equipped for survival in new, human-imposed environments. Land areas, watersheds, and coastal waters adjacent to estuaries impact upon estuarine sensitivities. Water resource managers are aware of the implied undesirability of rapid environmental changes and may be willing to release fresh water to downstream estuaries if a scientifically derived release schedule is available (28).

Reservoirs have usually been built because they met economic criteria demonstrating an ability for users to pay for the water. Capacity is planned to meet municipal, industrial, and other needs. The existing legal priority system gives municipalities first priority for acquisition of surface water, and they have preemptive rights over other users. The estuarine system has no specified legal basis for compe-

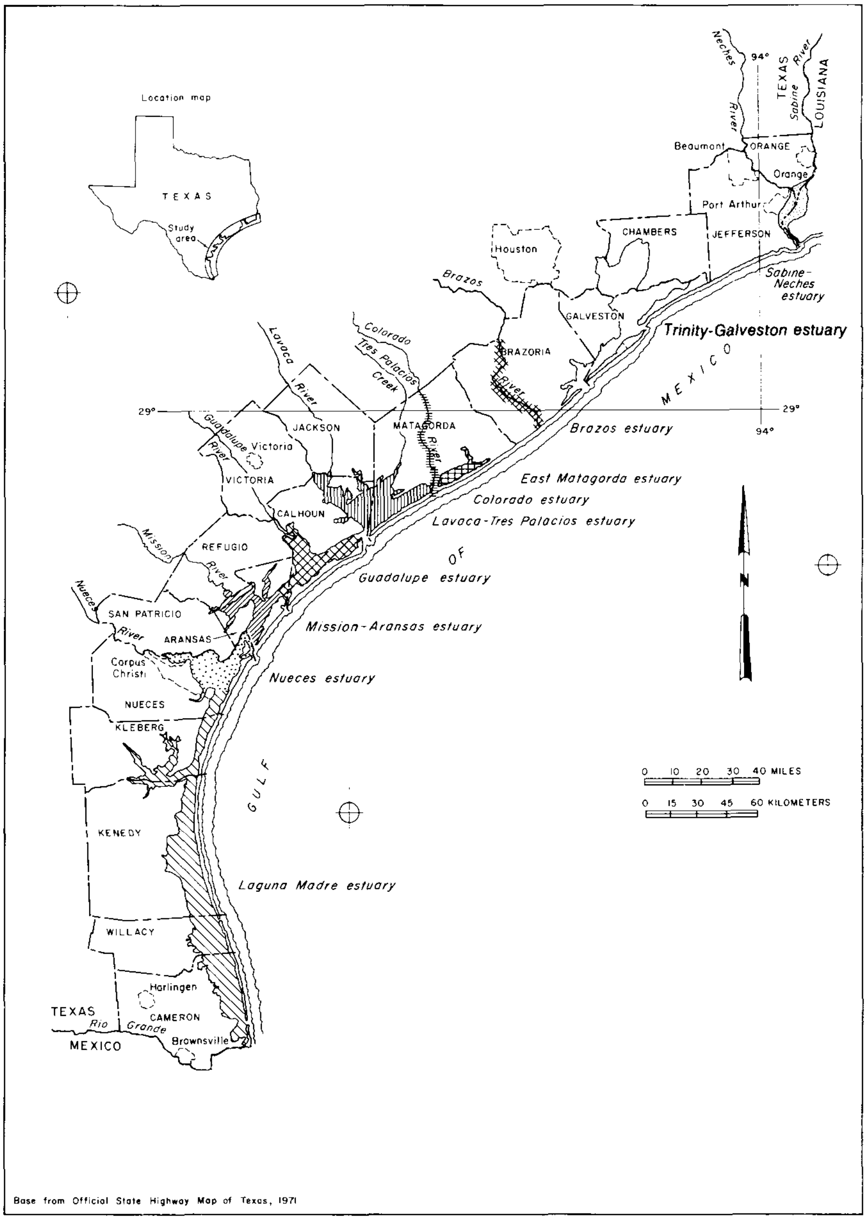


Figure 3. Locations of the estuaries.
Source: Texas Water Development Board.

ting for available fresh water. Such rights may be demanded for the purpose of protecting and preserving a valuable resource. The result could mean a conflict between the development goals of cities and the ecological goals for estuaries (28).

The investigation by the University of Texas indicates that if fresh-water releases for estuarine management become public policy, there is conflict with other demands. Each input data sequence indicated that fresh-water contributions from the Nueces River were required for approximately half of the summer months over the simulation period. Addition of Corpus Christi Bay as a legitimate fresh-water customer appeared to introduce a significant burden to the delivery capacity of the Lower Nueces River System. Under the conditions of the study, not even the introduction of Choke Canyon Reservoir saved the water system from experiencing repeated periods of system stress (28).

The State Legislature in 1975 enacted S. B. 137 which amended Chapters 1, 5, and 11 of the Water Code. This bill did three things: (1) It added as State policy "the maintenance of a proper ecological environment of the bays and estuaries of Texas, and the health of the related living marine resources" (1.003.1). (2) It directed the Water Rights Commission to consider estuaries: "In its consideration for a permit to store, take, or divert water, the Commission shall assess the effects, if any, of the issuance of such permit upon the bays and estuaries of Texas," (5.145). (3) It gave a more specific directive to the Texas Water Development Board in doing estuarine studies and required other State agencies to cooperate: "Staff shall.... investigate the effects of fresh water inflows upon the bays and estuaries of Texas." (11.062b.5). "The Board shall carry out comprehensive studies of the effects of fresh water inflows upon the bays and estuaries of Texas, which studies shall include the development of methods of providing and maintaining the ecological environment thereof suitable to their living marine resources. The studies shall be completed and the results published by December 31, 1979. The Texas Water Rights Commission, the Texas Water Quality Board, the General Land Office, the Parks and Wildlife Department, and the Texas Coastal and Marine Council are authorized and directed to assist and cooperate in all possible ways with the Board in this undertaking." (11.108) (34)

The Board contracted with the Remote Sensing Center of Texas A&M University (RSC) for a 1976 season-long remote sensing study of certain critical river deltas along the central Texas coast. The study was designed to provide the Board with a documentation of the extent, spread and species composition of several classes of marsh habitat (1).

The wetlands study sites comprised seven separate estuarine areas extending from upper Nueces Bay along the central Texas coast to the delta of the Colorado River. Each coastal wetlands area was formed by a unique set of natural processes and is different from the others (1).

The final report of the wetlands study points out that there is little or nothing that man can do to enhance the function of a natural wetlands area. Even with the best of intentions, the average coastal engineering project works to the detriment of ongoing natural processes. The wetlands are the most productive areas on earth. A greater weight of this planet's edible foodstuffs originates from a unit area of healthy wetlands than from any equivalent area elsewhere. The submersed vegetated areas also function as a nursery habitat for the juvenile population of fisheries species which we eat. Degradation of the nurseries or of the higher elevation vegetated areas results in a diminution of total fisheries productivity (1).

All of the wetlands study areas have been impacted by man's activities, but in varying degrees. The Guadalupe delta, because the river is in a relatively untouched state, behaves pretty much as a deltaic marsh should. The Lavaca delta appears to have been the most modified of the delta areas, and possibly is beyond effective reversal. The Colorado delta, undergoing the greatest amount of current change, is probably most amenable to recovery with appropriate management decisions (1).

The Nueces delta is trending downhill and will probably continue to do so because of commercial development. Turnstake Island and Pass Cavallo are recovering from earlier construction activities. The wetlands there seem robust and extensive. Unless further degradations occur locally or up-estuary, these areas can probably maintain their present productivity. The Aransas Pass area varies in that the northeast portion seems to be on the mend, while the southwestern area seems to be worsening (1).

The estuarine environment, under the proper circumstances, seems capable of renewing itself. If periodic flooding of deltaic wetlands is inhibited or prevented entirely, the value of maintaining a particular level of fresh-water inflow into the estuaries is unclear. Dredging, along with attendant spoil deposition, appears to be the greatest single damaging mechanism in the Texas coastal wetlands. Whatever may be the practical arguments for channelization or for the building of flood control dams, one can be certain that these construction activities will not be beneficial to marsh productivity (1).

Moseley (34) indicates that the Legislature must make some basic state policy decisions concerning the estuarine resources. As development continues, choices must be made. According to the Texas Water Development Board, the commercial harvest of fishery resources is greater in value from Texas than from any other Gulf state. Recreation and tourism associated with these estuarine systems generate more than $5 billion annually. The Board has preliminary estimates of required, sustaining annual gaged river inflows to major Texas estuarine systems of 6.1 maf (Table 3). Continuation of present trends for population increase, industrial development, and per capita rates of water use will put increasing stress on fresh-water inflows.

TABLE 3. GAGED RIVER INFLOWS TO MAJOR TEXAS ESTUARINE SYSTEMS (AMOUNTS IN THOUSANDS OF ACRE-FEET)

Major River(s)	Estuarine System	Minimum Monthly and Minimum Annual Gaged Inflows		Maximum Monthly and Maximum Annual Gaged Inflows		Average Historical Gaged River Inflows, 1941-74	Preliminary Estimated Sustaining Annual Gaged River Inflows a	b
Nueces River	Nueces-Corpus Christi	1 76	(Feb. 1942) (1962)	1,484 2,547	(Sept. 1967) (1971)	629	460	475
San Antonio and Guadalupe Rivers, Coleto Creek	Guadalupe-San Antonio	5 234	(June 1956) (1956)	1,564 4,529	(Sept. 1967) (1973)	1,726	1,200	1,200
Lavaca and Navidad Rivers	Lavaca-Matagorda	0 20	(Nov.1956) (1956)	850 2,024	(June 1973) (1973)	635	425	580
Trinity River	Trinity-Galveston	8 916	(Aug. 1956) (1956)	3,910 12,276	(Apr. 1945) (1945)	5,381	1,900	1,975
Neches and Sabine Rivers	Sabine Lake	28 2,287	(Oct. 1956) (1967)	6,938 22,547	(May 1953) (1946)	10,312	1,600	1,900
Annual Totals						18,683	5,585	6,130

[a]Based on salinity-inundation analysis.

[b]Based on fisheries analysis.

Source: Texas Water Development Board, *Continuing Water Resource Planning and Development For Texas,* Draft Report, Vol. 1 of 2, May 1977, page III-78.

Agriculture is the major user of water in Texas.

Agricultural Water Use

Agriculture, in contrast to manufacturing and most other uses, consumes a large part of its water withdrawals. There is less return flow to the water source from agriculture and less water available for reuse. The value in use of irrigation water tends to be low compared with municipal and industrial uses. In some areas of Texas, crop agriculture is almost wholly dependent upon irrigation for the moisture essential to plant growth. Rainfall is unevenly distributed and falls on some lands not suitable for crop growth. Sometimes water is transported to the more fertile areas, or deficient surface water is supplemented with ground water. Irrigated crop agriculture in Texas has been and will be limited by the volume and cost of available water (11).

Part of the water problem in Texas involves steady pressure for additional water supplies. Requisite land, labor, management, and capital are available. If only more water were available, additional dry land could be made productive. There is concern over the long run supply of water for agriculture as well as for all other water uses. Extraction of ground water in annual amounts far greater than recharge results in a steadily diminishing quantity of water remaining and a steadily increasing depth from which it must be drawn. In time, either well yield or pumping costs or both will prohibit continued irrigation. At this point, crop agriculture must shrink not only to its own economic detriment but also to the detriment of those parts of the State's economy related directly and indirectly to agriculture (11).

Cost of water increases as users must pump from deeper ground-water levels and as the energy for pumping increases in price. As water costs rise, it becomes necessary to economize on water use and to select those agricultural enterprises which can be profitable with higher cost water. Projected irrigation water use and projected irrigated acreage decline gradually.

Increases in water costs above certain levels will reduce agricultural use greatly but will affect all other uses only slightly. Agricultural irrigation is the marginal use and by far the largest user of the limited available quantities of water in Texas. The impact of any changes in costs of available water will affect agricultural irrigation much more than any or all other classes of uses taken together.

The economic problem of water does not rest on the physical quantity of available water alone but on the physical quantities available at particular costs. It is not enough to know that a million acre-feet of water are physically available. One must know what quantities, totalling a million acre-feet, are available at what cost for each quantity (11).

A news release from the Texas Department of Water Resources in January 1978 illustrates the changing situation in the Ogallala Aquifer in Hockley County (47). Report 214, "Analytical Study of the Ogallala Aquifer in Hockley County, Texas" charts the impact and future course of underground water depletion through the next 44 years and its effect on irrigation water production. The study shows that if present water use and irrigation practices are continued, the aquifer will decline from 3.5 million acre-feet of ground water in storage in 1974 to 2.0 million acre-feet in 2000 and 1.3 million acre-feet in the year 2020. Pumping lifts in wells throughout Hockley County range from about 50 to 275 feet. The study indicates that the range in pumping lifts in the county during the study period 1974 through 2020 will remain essentially the same because of decreasing saturated thickness and consequent diminished well yields. However, pumping lifts for specific wells will increase significantly. During the past three decades, the withdrawal of ground water has greatly exceeded the natural recharge of the aquifer. If this overdraft continues, the aquifer will be depleted to the point that it may not be economically feasible to produce water for irrigation.

The economic supply of ground water is not simply all of the water contained in the aquifer. It is modified by the costs required in lifting it to the surface. These costs in turn are affected by the depth to water, the efficiency of the aquifer in giving up the water it holds, the "draw down" or cone of depression resulting from pumping, the costs of energy, power and equipment, and the costs for well drilling, deepening, and casing (26).

Table 4 summarizes ground-water use for irrigation in 1974 by basins. The massive overdrafts in use of ground water for irrigation can be expected to continue under existing legislation and applicable legal decisions. As in Hockley County, irrigation pumping will continue as long as it is possible and profitable.

More than 35 million acres of U. S. farmland were irrigated in 1974 with the aid of energy-using pumps on farms and ranches. The largest acreage was in Texas, with 7,090,000 acres irrigated using ground water, 1,451,000 acres using surface water, and 256,000 acres using both (43).

Distribution Systems

Major water distribution systems include various sprinkler and flooding methods to put water on fields. Power units enumerated were electric, diesel, gasoline, natural gas, and LPG. Texas irrigated 6.3 million acres with power provided by natural gas, 1.9 million acres with electricity, and minor amounts with diesel, gasoline and LPG (43).

Pump efficiency is a measure of energy input to water output. A new irrigation pump has a reasonable potential efficiency of about 75 percent. Efficiency declines as wear occurs. Energy used for irrigation varies by efficiency of the pumping plant, the number of acres irrigated, quantity of water pumped for irrigation, water lifting height, and the amount of pressure required to operate the various irrigation distribution systems. When the lift is high and water applications are heavy, energy use increases (43).

Several irrigation distribution systems are used in Texas. A big gun system is a rather large sprinkler covering an acre or more at a setting. It is usually mounted on wheels and is moved either by hand or automatically across a field. A center pivot system is a line of pipe on wheels with numerous smaller sprinklers along the pipe which is fixed at one end. The pipe automatically pivots about the fixed end and usually irrigates about a 130-acre circle. Other sprinklers are side roll, skid, and hand move. Most surface distribution is by pipes with holes that let water run onto the field or by siphoning water from irrigation ditches with siphon tubes (43).

The amount of energy needed to operate the various types of distribution systems is proportional to the amount of pressure each system requires. Big guns require 165 pounds per square inch, center pivot, 100 pounds and surface distribution 5 pounds. Important factors that are considered in selecting a distribution system are terrain, soil type, and type of crop irrigated. Surface distribution is not practical on either sandy soil or rolling ground. Factors considered in selecting a particular sprinkler system include labor availability, field size, and type of crop, among others. In 1974, Texas irrigated 6,774,150 acres with surface systems, 439,880 acres by center pivot systems, 87,980 acres by big gun systems, and 1,495,590 with sprinkler systems (43).

TABLE 4. WATER USE BY GROUND-WATER SOURCES, BY BASINS, 1974

Basin	Municipal	Manu-facturing	Steam-Electric	Irrigation	Mining	Livestock	Total
	----------	----------	----------	000's Acre-Feet	----------	----------	----------
Canadian River	18.8	30.5	6.0	1,915.5	4.8	10.3	1,985.9
Red River	39.4	10.6	0	2,015.9	4.2	14.7	2,084.8
Sulphur River	8.2	1.2	0	0	0.5	1.0	10.9
Cypress Creek	9.1	1.7	0	[1]	1.2	0.7	12.7
Sabine River	27.5	19.1	0	1.9	1.9	2.1	52.5
Neches River	39.5	85.9	0	9.7	2.8	2.1	140.0
Neches-Trinity Coastal	5.3	2.8	0	0	0.3	0.1	8.5
Trinity River	61.9	13.5	6.7	20.9	4.3	4.4	111.7
Trinity-San Jacinto Coastal	9.4	6.9	0	4.7	1.7	[1]	22.7
San Jacinto River	216.1	217.1	13.8	120.0	16.2	0.4	583.6
San Jacinto-Brazos Coastal	42.1	21.8	0	16.2	2.5	0.2	82.8
Brazos River	94.5	17.0	9.2	3,782.6	27.5	19.2	3,950.0
Brazos-Colorado Coastal	8.1	3.5	0	61.7	4.2	0.3	77.8
Colorado River	50.1	7.4	1.3	910.5	76.0	20.9	1,066.2
Colorado-Lavaca Coastal	2.7	4.1	0	115.9	0.2	0.1	123.0
Lavaca River	5.9	1.0	0	230.8	1.1	0.6	239.4
Lavaca-Guadalupe Coastal	1.8	[1]	0	34.1	0.4	0.1	36.4
Guadalupe River	28.3	6.3	5.1	4.9	0.8	4.4	49.8
San Antonio River	155.6	16.4	2.3	36.8	3.3	3.9	218.3
San Antonio-Nueces Coastal	7.3	0.6	0	6.3	0.5	2.3	17.0
Nueces River	18.5	2.5	0.6	396.4	1.6	14.8	437.1[2]
Nueces-Rio Grande Coastal	15.5	2.0	0	25.7	2.5	8.9	54.6
Rio Grande River	103.2	14.5	7.8	693.9	20.2	16.4	856.0
Total	968.2	486.4	52.8	10,404.4	178.7	127.9	12,221.7

[1]Less than 50 acre-feet.

[2]Includes 2.7 acre-feet designated as "Other."

Source: Texas Water Development Board, *Continuing Water Resource Planning and Development For Texas,* Draft Report, May 1977.

Agriculture is the major user of water in Texas (Tables 4 and 5). In 1974, irrigation used 10.404 maf of ground water out of a total 12.222 maf or 85 percent. Surface-water use was substantial for municipal and industrial purposes, but agriculture used 2.681 maf of the total 5.121 maf, or 52 percent. On a combined basis, agriculture used 76 percent of all the water used in Texas in that year (50).

The Texas Water Development Board in the Publication Draft, "Continuing Water Resources Planning and Development For Texas," May 1977, compared present and projected water use by categories. While all other use categories were projected to increase by the year 2000, agriculture was projected to decrease by 5.471 maf. This projected decline is greater than the total for all other uses in 1974 (50).

The major cause for the decline in irrigation will be ground-water depletion. The withdrawal and use of ground water have increased to the extent that aquifers now supplying major areas of Texas will be seriously depleted of fresh water and will suffer water-quality deterioration.

Agricultural Water Conservation

California is a major agricultural state which relies on irrigation and which has been pressured by drought during recent years. One result has been increased attention to conservation methods that help save water and energy and reduce waste. A California Department of Water Resources publication summarizes methods for reducing agricultural water use (56). Each of the suggested conservation practices offers some potential for consideration in Texas.

1. *The irrigation method*
   Sprinkler systems generally produce higher farm irrigation efficiencies than those for comparable gravity irrigation methods (border, basin, or furrow). A farm irrigation efficiency representative of gravity irrigation systems in California is estimated at 58 percent and sprinkler systems at 76 percent. Unavoidable on-farm water losses occur with all irrigation methods and systems.
2. *Irrigation scheduling*
   To efficiently schedule irrigation water, a grower must understand climate, soils, crops, and complex management factors that influence irrigation scheduling decisions. If he misjudges any of these factors, he may irrigate too often or not often enough. A knowledge of water-use rates for various crops at various growth stages and localities

TABLE 5. WATER USE BY SURFACE WATER SOURCES, BY BASINS, 1974

Basin	Municipal	Manu-facturing	Steam-Electric	Irrigation	Mining	Livestock	Total
	000's Acre-Feet						
Canadian River	12.0	3.7	0	0.4	0.1	5.1	21.3
Red River	42.5	4.4	7.8	37.3	1.0	20.0	113.0
Sulphur River	14.2	28.5	0.2	0	¹	7.9	50.8
Cypress Creek	3.2	153.1	10.6	0.3	0.1	4.0	171.3
Sabine River	17.8	65.6	3.7	8.1	0.3	9.9	105.4
Neches River	17.9	108.8	6.3	26.3	1.1	9.8	170.2
Neches-Trinity Coastal	18.8	69.6	0	261.6	6.1	1.1	357.2
Trinity River	366.1	115.7	31.4	68.1	10.5	25.0	616.8
Trinity-San Jacinto Coastal	0	48.2	0	28.0	0	0.3	76.5
San Jacinto River	65.9	91.5	2.6	0.4	0	3.5	163.9
San Jacinto-Brazos Coastal	7.2	82.7	0	155.2	0.1	1.4	246.6
Brazos River	129.2	214.2	37.6	68.0	10.6	45.3	504.9
Brazos-Colorado Coastal	¹	8.4	0.	152.2	4.4	2.1	167.1
Colorado River	119.9	14.0	19.7	134.3	12.9	15.0	315.8
Colorado-Lavaca Coastal	0	4.0	0	86.6	0	1.1	91.7
Lavaca River	0	0	0	80.3	0	3.7	84.0
Lavaca-Guadalupe Coastal	1.4	22.2	0	42.2	0	1.2	67.0
Guadalupe River	4.2	31.0	2.0	4.9	0.5	6.0	48.6
San Antonio River	0	0.3	16.9	21.3	0	2.2	40.7
San Antonio-Nueces Coastal	4.3	13.0	0	¹	0.2	0.6	18.1
Nueces River	1.5	0.7	3.2	68.8	0	1.6	75.8
Nueces-Rio Grande Coastal	94.6	32.2	4.3	997.6	0.1	1.0	1,129.8
Rio Grande River	42.0	0.8	2.0	438.8	0.3	0.4	484.3
Total	962.7	1,112.6	148.3	2,680.7	48.3	168.2	5,120.9

¹Less than 50 acre-feet.

Source: Texas Water Development Board, *Continuing Water Resource Planning and Development For Texas*, Draft Report, May 1977.

is essential for scheduling irrigation in a manner that will minimize water losses.

3. *Good Drainage*
   The management of excess water, either surface or sub-surface, is a vital consideration for on-farm, district, and basinwide interests. Land leveling or smoothing should be based on both efficient application of irrigation water and management of excess surface water. Subsurface drainage problems generally result from soils becoming saturated by perched or shallow water tables.
4. *Salt management*
   Salinity is one of agriculture's most complex production problems. If excessive salts from irrigation water or high water tables are permitted to accumulate in the soil, crop production is adversely affected. If no remedial measures are taken, economic crop production will eventually become impossible. The proportion of applied irrigation water required to maintain acceptable soil moisture salinity will vary with different crops, different irrigation waters, and acceptable crop losses.
5. *Rainfall utilization*
   Potential water saving from more effective use of rainfall on irrigated land varies widely with rainfall amounts, timing and intensities, soils, and cropping patterns. Even under optimum conditions, only modest savings could be expected through improved use of rainfall. There are very limited situations where it is possible to increase preseason soil moisture storage.
6. *Weed and phreatophyte control*
   Water losses by weeds in crops are highest in row crops and orchards that have not attained more than 60 percent ground cover. Water is also lost when water-loving weeds (phreatophytes) are permitted to grow in open ditches or in poorly drained areas. Water losses can be reduced by lining ditches, replacing open ditches with pipelines, and draining areas where the water table is high.
7. *Seepage control*
   About 10 percent of the water diverted for agricultural use is lost to seepage from on-farm head ditches and from district canals and laterals. New irrigation districts, or those rehabilitating out-dated facilities, tend to eliminate open ditches by installing closed-pipeline water-conveyance systems.
8. *Evaporation and transpiration suppression*
   The control of evaporation and transpiration

has some potential for water savings. Evapotranspiration can be reduced by "stressing" the plant, limiting soil moisture. The feasibility of reducing water use by limiting soil moisture varies with (1) the crop, (2) the growth stage, (3) the farmer's ability to schedule and manage irrigation, and (4) the cost and availability of water.

9. *Crop factors*

   Seasonal water requirements could be reduced if crops were planted with water savings as a prime consideration. For example, water can be saved by planting short-season crops, low water-using crops, and deep-rooted crops. While potential water savings can be significant, farmers generally select crops on the basis of market demand which is not always compatible with water-saving objectives.

10. *System automation*

    Automatic water-control mechanisms which regulate water levels in major canals are in use in some areas. Such automatic systems can produce water savings through more accurate diversions and allocations of water. On-farm automatic systems include mechanisms that start and stop power units, and thus water flow, at predetermined times. Such controls help conserve water by preventing excessive water application. By contrast, manual systems might not be turned off at night or at other inconvenient hours.

11. *Land use*

    Water conservation is also related to the efficient use of croplands. Selecting crops on the basis of soil and slope conditions increases the potential for high irrigation efficiency and high crop yields. Planting the wrong crops on marginal land often results in wasted water.

12. *Institutional*

    All agencies with responsibility for water management should work together in developing coordinated systems and operating procedures that will (1) permit conjunctive use of surface and ground water; (2) improve the process of delivery of water and the capture and allocation of return flows; (3) reduce overall energy use; and (4) enable expansion of beneficial uses of the developed water supply, including improved instream uses.

In view of the seriousness of the water problem for irrigated agriculture in Texas, research is being conducted to improve efficiency of agricultural water use. In addition to the opportunities listed above for conserving water, research in the areas of (1) row damming to collect rainwater and irrigation water, (2) mobile trickle irrigation systems with very low pressure requirements, (3) night sprinkling cotton with saline water, and (4) drought resistant varieties that indicate dramatic improvements in agricultural water use efficiency. The results of this work may be to extend the economic life of the ground-water supplies thus maintaining for a longer period of time the regional economies dependent on irrigated agriculture.

However, it is important to emphasize that ground-water withdrawal greatly exceeds natural recharge in Texas. Thus, the overall conclusion remains the same. Texas is approaching that time when very significant reductions in ground-water withdrawal will be forced due to either exhaustion or pumping costs, or both.

Metropolitan Water Use


Costs for providing metropolitan water services are escalating rapidly.

Estimates of the population of Texas counties and metropolitan areas for July 1, 1976, indicated a continued rapid growth. Metropolitan areas had 9,820,100 persons and nonmetropolitan areas 2,666,800 on this date, according to the Bureau of the Census. These figures show that 78.6 percent of the Texas population lived in metropolitan areas on that date. The increase from 1970 to 1976 in metropolitan areas was 1,136,600 persons or 13.1 percent and in nonmetropolitan areas 151,700 persons or 6.0 percent. These trends are expected to continue (42).

The costs of providing metropolitan water services are escalating rapidly. Urbanization creates drastic environmental changes. Natural surfaces are dotted with buildings and water-absorbing land is sealed with paving that accelerates and augments runoff. Some water flows are diverted, withdrawn, used, and discharged back to their watercourses as effluents. At the same time, people concentrated in high-density complexes desire the amenities of open space and water-related recreation (53).

Some water managers anticipate a continuing increase in daily per capita use of water by urban dwellers. Robert Van Dyke, General Manager of the San Antonio City Water Board, made this forecast at the 1974 Water For Texas Conference:

"Coupled with the increased urban population is an ever-increasing daily per capita use of water by our city dwellers. A quarter of a century ago, metropolitan water systems were designed on the basis of 100 gallons per capita per day. This figure has increased to approximately 150 gallons per capita per day today, and it is anticipated that it will rise to over 200 gallons per capita per day by the turn of the century." (57)

San Antonio depends upon ground water from the Edwards Aquifer for its present water supply. It has Federal protection against contamination of the Edwards Aquifer under the Safe Drinking Water Act, Public Law 93-523. Van Dyke states that San Antonio will ultimately supplement its present ground-water supply with surface waters from the San Antonio and Guadalupe River Basins. He approves of the top position accorded municipal use in the statutory schedule of priorities. The Legislature has provided that all appropriative rights acquired after 1931 are subject to future municipal needs and may be taken without compensation. He anticipates that changes in present ground-water legislation will occur and that municipal interests will require protection (57).

Houston and Dallas/Fort Worth have planned for future water needs. They have resources capable of meeting requirements from increased population for from 20 to 30 years. Plans for the future tend to assume increased per capita consumption of water based on available supplies and low prices. A considerable gap exists between present water prices and the point where price will call for water management and conservation. It is likely that increased energy costs for transporting water will require efficiency in reservoir operations in all pumping operations (18).

The National Water Commission takes a broader view of the most pressing metropolitan water management problems. The primary objectives are (1) to provide the three basic water services — water supply, wastewater collection and treatment, and storm water management — efficiently and effectively, (2) to make efficient use of scarce water resources, and (3) to lessen the disruptive and degrading effect of urban growth and development on the urban environment and water quality (53).

Providing Water Services

A considerable investment has been made and is being made for developing water services. Some monetary costs result from capital investments that government or business must make in order to provide for their water needs, especially reservoirs, aqueducts, and pipes. In a large, sprawling city, a high proportion of investment is in distribution and collection of water within the city. Costs are substantial for the pipes which collect sewage. Other costly items in a complete water system are sewage treatment plants, storm drains, and flood control dams. The most easily exploited water sources have already been developed. Sources requiring more complicated and costly development must be utilized in the future. Increased water consumption from any source requires comparable increased investment for sewage treatment (33).

When water system facilities are built with enough foresight, many social benefits accrue to balance the costs of the facility. Reservoirs developed with recreation in mind provide entertainment and income for an entire region. Similarly, environmental costs result. Changes occur throughout the whole ecosystem when a river is restrained by dams or drained by gigantic withdrawals (33).

Texas laws creating and protecting rights to the use of water fail to give adequate recognition to social or noneconomic values in water. The protection of noneconomic values lies in the hands of private citizens. The National Water Commission believes that State laws should be improved to provide greater protection of social or noneconomic values in water. Specifically, legal water rights should be created in the public for such uses as esthetics, recreation, and fish and wildlife propagation (53).

Municipal Water Conservation

Financial benefits must be associated with conservation if people are to be persuaded to conserve water. When water-saving toilets become less expensive than present ones, people may be more willing to accept a change in their water-consumption habits. The cost of water can be increased to inhibit consumption, and property taxes can be reduced when water-saving devices are used. Penalties can be levied on those using more than an acceptable amount of water to increase the motivation for change (33).

In every society some individuals reject an innovation simply because it is new. An innovation may be more easily adopted if it closely resembles something already accepted in the culture. Water-saving devices must be attractively designed and not differ too radically from equipment already familiar to our society. If water-saving devices are tried in a store or display area, the possibilities for their acceptance are improved. A drought or threat of a drought also causes a larger number of people to try new mechanisms (33).

The power of the advertising industry in making and shaping public attitudes is well known. Increasing amounts of money are being spent on serious campaigning to increase water conservation. The major plumbing manufacturers are beginning to advertise their recently developed lines of water-conserving fixtures in national trade journals. There is a market for these items in areas experiencing water shortages and wherever building owners and managers have become sensitive to the increased costs of water and the energy needed to heat and pump it. Developers have learned that prospective customers are impressed with such things as low-flow-rate shower heads, water conserving toilets, hot water pipe insulation, and landscaping designed to reduce the need for irrigation (33).

Water supply systems in many locations are urging their customers to use less water. Reasons include failure of bond issues to finance further expansion, pressure from public utility commissions, mismatch between water supply and sewage treatment system capacities, apprehension about the possibility of water rationing, and customer resistance to increased utility rates. Over-taxed sewage treatment agencies also have begun programs on behalf of water conservation. Most areas in Texas can expect to be affected by water shortages, overloaded sewage systems, increasing energy costs, and higher utility rates. The essential ingredient for the adoption of conservation is education which is meaningful to all segments of our society (33).

Houston city officials estimated in January 1978 that 10 to 20 percent of the city's water production is lost because of main leaks and inoperative meters. About 60 percent of these water main breaks are caused by electrolysis, a year-round problem. The water division of the city receives no tax dollars and is limited in what it can do by the amount of revenues from the sale of water. The mayor of Houston ranks main breaks and leaks among the city's top 10 problems because they cause inconvenience, property damage, and losses of millions of gallons of water annually (58).

Reuse of Waste Water

Two principal forces are at work which are bringing about an increase in the reuse of water — (1) the increasing costs associated with water and (2) environmental restrictions imposed by water quality control authorities (61).

The cost of raw water in reservoirs that are being planned now will be from five to ten times greater than the cost of water in reservoirs completed as recently as two years ago. Reservoirs are being located farther from the point of use. These factors, plus the general level of inflation in the economy, point to more and more increases in the cost of water. The higher the cost of water, the greater the incentive to make multiple uses of water (61).

The other force at work in water reuse is the State and Federal system of environmental controls. As the Federal Environmental Protection Agency and the State Water Quality Board achieve required standards in waste discharge, the waste water becomes suitable for reuse. In many situations involving industrial use, closed systems, and recycling are or will be mandatory under EPA standards (61).

A city saves water when it recycles a part of its sewage effluent through its water supply reservoirs. Sewage return flows are stable, and their introduction into a reservoir increases its firm yield by approximately the amount of return flow. A more common way to reuse treated sewage effluent is for industrial or irrigation purposes. As levels of treatment increase and costs rise, the need to sell treated effluent to offset treatment costs increases. The city may deliver water for these purposes from the outlet of its sewage treatment plant. In some cases, it may use the bed and banks of a stream to deliver treated water to a purchaser downstream (61).

The case for reuse should not be overstated. The extent to which a city may recycle through a water supply reservoir is severely restricted. Careful consideration must be given to the effect on the reservoir during drought periods when dilution from natural streamflows is significantly lowered (61).

The law on the subject of reuse is based on irrigation return flows. The cases indicate that an appropriator has the right to recapture his return flows and reuse them as long as the reuse is at the original place of use and for the purpose for which the water was originally appropriated. This is true even though downstream appropriators have developed uses relying on the return flows and have used them for substantial periods of time. The first appropriator may make his practices more efficient and reduce waste by recapturing his own drainage and seep water (61).

Municipal recycling of treated sewage effluent through a water supply reservoir requires careful planning. The terms of the city's permit may require Water Commission approval for a change in the point of discharge. Also, when the city discharges its effluent into a reservoir, it loses ownership and control of the water unless special permission has been obtained from the Commission. When return flows are discharged, they lose their identity as appropriated water and become subject to the rules governing streamflow. If the city making the discharge owns the reservoir, and the reservoir permit is the senior appropriative right, the city would be entitled to recapture its discharge under that right. But if more senior appropriators can utilize the increased flow, they would have the first right to capture the discharge (61).

A city that desires to sell its treated effluent for industrial or irrigation use rather than recycle it through a reservoir may have other problems. An amendment to its permit may be required since such a use may involve both a change in the purpose of use and a change in the place of use. If the city desires to sell the effluent to a purchaser downstream, it must obtain a permit from the Commission to use the bed and banks of the stream for this purpose (61).

The legal position of cities using ground water as a source of supply is somewhat different from cities with permits or certified filings. Ground water is private property under Texas law and is not regulated by the State to any significant degree. A city using ground water would seem to have greater freedom to reuse its sewage effluent and to change the place and purpose of use so long as it does not discharge the effluent into a stream. Unless the Commission has authorized the use of the stream for conveyance purposes, sewage effluent becomes a part of the stream whether or not the water originally came from surface or underground sources (61).

A city that desires to reuse or sell its treated effluent should analyze its legal position carefully and obtain the necessary permits as early as possible. The Commission will take into consideration the interests of downstream rights which have been developed in reliance on previous discharges. For that reason, it is better to obtain the necessary permits before the downstream use develops (61).

Water has been widely reused by industries as well as municipalities. Cooling towers with multiple recycling are common. Thermal pollution restrictions and chemical contamination problems have accelerated efforts by industry to improve the quality of water applied to cooling towers. Coagulation, sedimentation, and softening have been practiced prior to application to cooling towers. This permits recycling water more times, evaporating more, and returning less to the stream (18).

In some cases, industrial water has been so cheap that opportunities have been overlooked for reuse in plant processes. Water of extremely high quality has been discharged to the sewer after very slight contamination by highly sophisticated manufacturing processes. Substantial savings in water costs have been demonstrated in manufacturing facilities such as food processing and refineries when attention was paid to water reuse or conservation (18).

Recycling or reclaiming waste water has great potential for increasing the amount of water available for use. Waste water which is treated in the tertiary, or three-stage process, emerges crystal clear, colorless, odorless, and free of micro-organisms, and it is pure enough to drink. This scientific cleansing process accomplishes in a short time what nature achieves in a longer period. Because attitudes toward human wastes arouse feelings of repugnance in a large part of the general public, acceptance of artificially treated water has sometimes been poor. Feelings of aversion to reclaimed water are especially prevalent when it is used for purposes which involve contact with the body. A greater acceptance has been found when such water is used for residential lawns and irrigation of golf courses (33).

The net effect of the Texas statutes and court decisions appears to be that an appropriator has a right to recycle and reuse water as he pleases so long as he does not change the place of use or the purpose for which the water was appropriated. Thus, most industrial recycling presents no particular water right problems and can be effected without Commission approval. The same would be true of direct recycling of municipal wastes (61).

Water Pricing

In the past, water has been generally so abundant, relative to the demand for it, that it has been provided at little or no cost to users. This situation is now changing. Water has become a resource that is relatively scarce. The land, labor, capital, and energy resources needed to convey water to places of useful application and to collect and treat wastewater also are scarce (35).

When a resource is scarce, society finds it necessary to apportion use in such a way as to obtain maximum beneficial returns. The limited supply of usable water should be allocated among the uses where it will be most productive. In this country, prices are usually found to provide the most effective allocation system. A price is charged for water and water-related services, which causes the scarce water resource to be shifted to its most productive uses. Each user continues to use more and more water until the value to him of the last unit equals the price he is charged for water. He will not use additional supplies because the cost will exceed the value he receives (35).

Pricing also functions to induce production of the desired level of supply. Given the limits on national, state, and local resources, output of one commodity can increase only if resources are diverted to it from production of something else. Consumer benefits from one action must be compared with alternative products and services that must be foregone. Prices inform producers of consumers' relative desires for a commodity and indicate the extent of desired production (35).

Water is a mobile resource, typically used and reused until it is evaporated or returns to the sea. The same unit of water may be used for a number of uses within the stream, such as recreation, fish production, waste dilution, and navigation. The water may be diverted from the stream to be used for industrial, urban, or agricultural uses. These supplies may return to the stream diminished in quantity and degraded in quality. They are often changed in time of flow and in location from the original diversion. These substantial interdependencies should be recognized in the management of water supply. A use that reduces quality, delays flows, or diverts water to a different location makes it potentially less useful to others and should be charged accordingly (35).

A competitive market alone does not result in optimum utilization of water. The economic effects extend beyond the buyers and sellers involved. However, the use of improved pricing systems within established legal and administrative frameworks could enhance the efficiency of water use. The reform of present legal systems to provide for exchange of water rights under specified conditions would also be useful.

Present water pricing is far from the ideal desired for an effective pricing system. Pricing by public agencies is typically based on revenue considerations. The primary aims are fiscal soundness and harmonious customer relations. Pricing to provide efficient checks and balances on water allocation and use are not given high priority. Pricing is sometimes below the cost of amortizing and operating the water system. Funds are then sought elsewhere to cover the deficiency (35).

Major cities have the necessary economic and political power to develop water supplies in advance of need. Sometimes these temporary surpluses are sold to suburban towns which are part of the cities' metropolitan area. In December 1977, the City of Dallas was accused by a State legislator of charging "unreasonable" water rates to 18 suburban towns. The Texas Water Commission has final rate-making authority and can use any reasonable basis for fixing rates (8).

Dallas wishes to sell water on a utility basis, obtaining a "fair rate of return on investment," not only the investment as it currently stands, but the investment required to furnish peak-load water to the suburbs by the year 2000. The suburban cities contend that Dallas should sell water to them on a debt retirement basis under which the customer cities would be credited for helping pay for the Dallas water impoundment, treatment, and delivery system (8).

Since water is becoming scarcer and more costly to develop in Texas, prices paid for water will continue to rise. One objective of water management is to increase the efficiency of existing equipment and facilities so that costly new investments can be deferred. While increases in the price of water alone may not significantly reduce water consumption, changing to a higher rate structure may complement other measures taken to conserve water (33).

Industrial Water

Projections of water requirements for manufacturing were developed by the Texas Water Development Board, identifying the 1974 water use of an industry and then relating these 1974 base-year demands to four major factors affecting future water use. The factors are changes in employment, labor productivity, recirculation, and technology. Rapid changes in recirculation rates and in the efficiency of water use in manufacturing have demonstrated that the effects of increased output on water demands may be wholly or partially offset by changes in the recirculation rates and technology (50).

A single mathematical equation was used to describe the relationship between base-year water use and those factors influencing future demands. Manufacturing water demands were derived and projected by decades through 2030. The procedure was to develop estimates of base-year water use by county and by industry sector and then, using current and detailed data, to compute projections for each of the four factors influencing future water demands. Projections of changes in recirculation and technology incorporated the impact of recent water pollution control legislation. These projections assumed increasingly restrictive effluent standards and probable increases in the price of fresh-water withdrawals (50).

Water For Mining

Mining was categorized into fuels, metals, and nonmetals by the Board for purposes of analyzing the future water needs of this important sector of the Texas economy. The crude petroleum and natural gas producing industries utilized 163,572 acre-feet of fresh water in 1972. Mining of metals used 3,683 acre-feet. Nonmetals included sulfur and salt mining, clay, sand and gravel, and crushed stone and used relatively small quantities of water (50).

Availability of water is a factor to be considered in all mineral fuel resources development. Comparatively large amounts of water are needed for mining lignite, coal, and uranium. Constant spraying of haul roads for dust control requires a reliable source of water. If strip mining is practiced, water is required for reclamation of the land. Processing of the different ores requires varying amounts of water, some of which can be recycled, but the net effect is a loss of water.

The future growth of the mining industry in Texas will be determined by its competitive economic advantage relative to other mineral-supplying areas in the world and by its ability to locate economically exploitable ore-bodies within the State. Water as an input to the mining and smelting industry, though essential in relatively small quantities per unit of output in both weight and value terms, rapidly exhausts its productivity as larger quantities are used per unit of output or income. The industry can compete readily for small quantities of water, and water availability usually has not limited the mining sector of the Texas economy (50).

Water For Electric Power

Water requirements for existing steam-electric power plants (Tables 4 and 5) were based on actual plant operating data. Likewise, water consumption requirements for announced power plants and for power plants currently under construction were based on actual plant design data. For all future additions in installed capacity it was assumed that half the additions would be nuclear, with the remainder being a mixture of coal and lignite fired power plants. The mixture of coal and lignite fired power plants was altered by basin to reflect lignite resource availability. Projections are based on the assumption that the plants will operate at an average load factor of 60 percent (50).

Recreation

The rapid increase in the use of the State's water resources for water-oriented recreation is a reflection of growth in population, income, and leisure time. Based on projected increases in these variables, the demand for water-oriented recreation in the State is projected to increase by the Board. Reports show that 41.7 million visitors participated in recreational activities at Corps of Engineers water projects in Texas during 1976 as compared with 28.9 million in 1973, an increase of approximately 44 percent. The Board assumed that recreation is a nonconsumptive use of water and that water resources projects developed for other purposes also will supply the water needed for recreation (50).

Rural Water Supplies

As the population of Texas has grown, the State has become more industrialized, with large cities having high population densities. A specialized industry has developed which captures and stores raw water in rural areas and transports this water to urban areas for treatment and use. A significant population still resides in rural areas and is increasing after decades of decline. These areas vary in population density from small communities to individual residences. Rural area residents require a dependable supply of safe, clean drinking and household water. The Federal Safe Drinking Water Act of 1974 (PL 93-523) specifies standards for public water supplies that many rural and small community systems have not met in the past (50).

A combination of individual household systems and privately owned corporations supply water to small communities and rural residences. As of June 1976, rural water supply corporations served an estimated 600,000 to 700,000 persons, or about 5 percent of Texas population. The rural water systems have difficult problems of economics, quantity, quality, and increased regulations in supplying water to their customers. The relatively small size and low density of service area population result in high costs per customer. Rising prices of inputs have increased costs of operating distribution systems and treatment plants in recent years (50).

The Federal Safe Drinking Water Act was implemented in Texas in June 1977. This act establishes new quality standards for drinking water and redefines public water systems. It is estimated that 10,000 existing "private" systems in Texas will be reclassified as "public" water systems and be subject to the water quality standards specified in the Federal Interim Primary Standards. By the new definition, the act can be construed to include restaurants, service stations, hunting camps, camp grounds, and farms and ranches. Rural water systems have difficulty meeting established quality and operational requirements, because these systems serve relatively small numbers of users and do not have the cost advantages of larger systems (50).

More efficient use of existing water resources is imperative to avoid the recurrence of dust storms such as the ones in the 1930's.

Drought Effects

Texas is wedged between the warm waters of the Gulf of Mexico to the south and east and the high plateaus and mountain ranges to the north and west. Its climate is characterized by extremes in rainfall and temperature and by catastrophic weather events. A continental type climate, marked by rapid changes in temperature, is prevalent here. The interaction between warm, moisture-laden air from the Gulf of Mexico and drier, relatively cooler, continental surges of air from the north and west is responsible for most of the climatic patterns and the water supplies of the various parts of the State (50).

The uneven distribution of rainfall over Texas both seasonally and annually, combined with seasonal occurrences of hailstorms, tropical storms, hurricanes, tornadoes, and floods make Texas weather an extreme variable. The erratic and unpredictable nature of extensive droughts, as well as highly variable rates of precipitation and evaporation, add to problems of water management (50).

Mean annual precipitation ranges from less than 8 inches in extreme West Texas to more than 56 inches in extreme East Texas (Figure 4). Generally, rainfall increases from west to east across Texas, with the average increase being about 1 inch every 15 miles. By contrast, annual rainfall totals are observed to vary little from north to south across the State (50).

Higher temperatures in summer, caused by a greater amount of solar radiation reaching the earth's surface and coupled with low humidities, lead to a greater degree of evaporation of surface water. This is an important consideration in reservoir design. When temperatures are high and humidities are low, water consumption by people, plants, and industry are higher than at other times of the year (50).

The amount of lake surface evaporation is influenced by air and water temperature and wind movement over the surface of the water. Mean annual net evaporation rates are zero inches in East Texas near the Sabine River, where abundant rainfall offsets lake surface evaporation. They are almost 100 inches annually in the Trans-Pecos, where rainfall is low and evaporation rates are extremely high. During wet years, when rainfall is abundant, net lake surface evaporation rates are low. During years of drought, evaporation from lakes and transpiration of growing vegetation are high and the water supplies are increasingly depleted (50).

Like the rainfall distribution in Texas, lake surface evaporation rates remain fairly uniform from north to south across the State. While evaporation is largely offset in eastern Texas by abundant rainfall, western Texas usually suffers high evaporative losses with low rainfall. Lake surface evaporation is a continuous process, even in the more humid areas of East Texas. Maximum evaporation occurs statewide in the summer months (50).

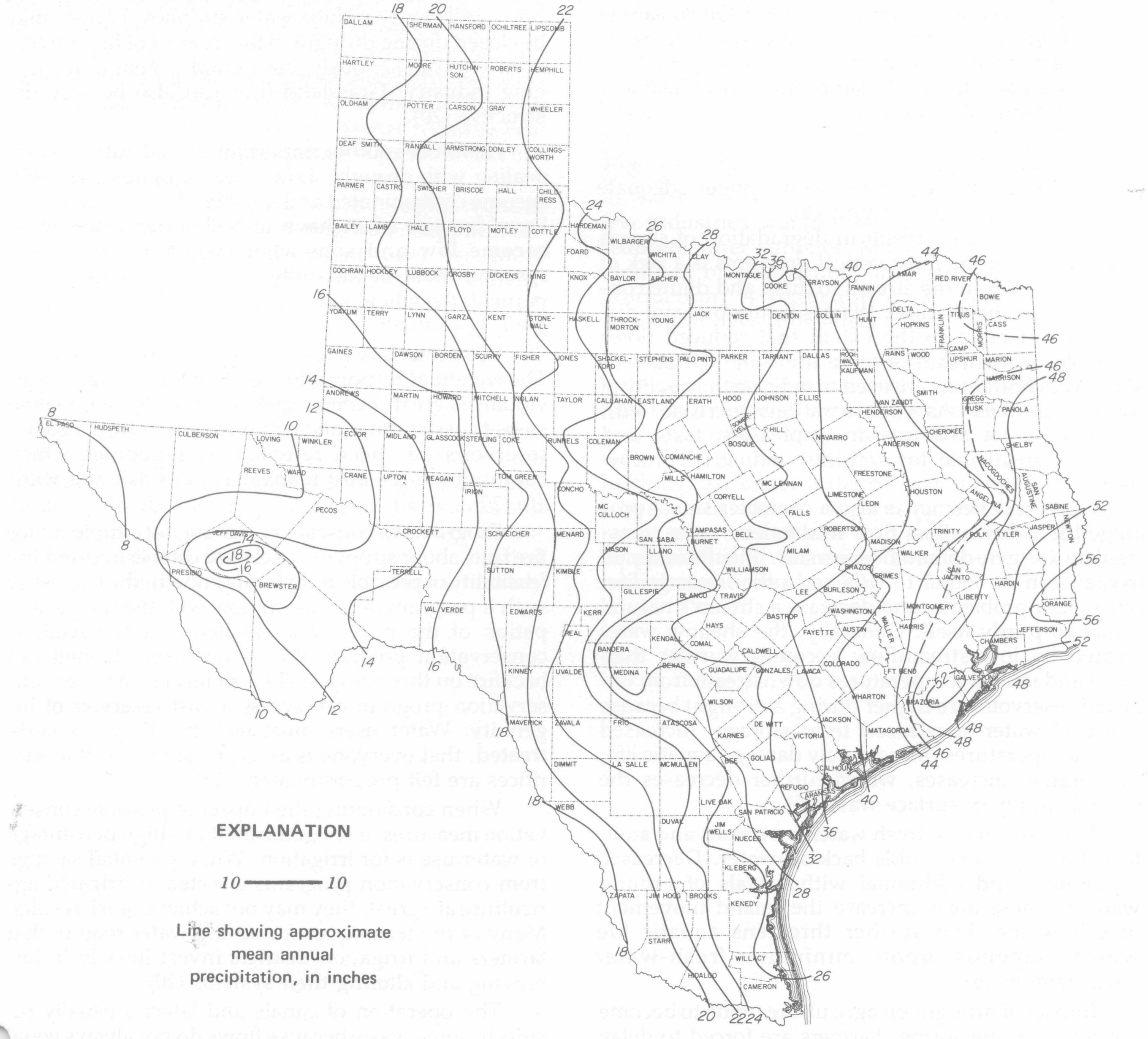


Figure 4. Mean annual precipitation, in inches.
Source: U. S. Department of Commerce
Climatography of the United States No. 81 (Texas).

Water needs are augmented by irrigation to sustain plant life in areas where there is insufficient rainfall and where evaporation rates are high. Evaporation parameters are a part of the data for calculating water supplies from existing and potential reservoirs (50).

Drought interrupts the flow of water supplies and increases the consumption requirements from water in storage. Man can cope partially with drought by installing additional wells for immediate use or by constructing surface water storage facilities and storing surface water supplies for emergency use. Longer droughts tend to require water conservation measures by all users (50).

When a drought occurs, the effect on the State's water resources continues to escalate. Streamflow decreases; ground water levels drop; reservoir storage is depleted; and water quality is degraded. One means of determining the seriousness of the situation is by comparing current streamflow with the historical record. Ground-water levels can be another indicator of drought. Many shallow wells provide adequate water supplies for domestic use in normal years, but water table levels drop quickly with continued drought. Then wells go dry, or yields are no longer adequate even for a home water supply (6).

Water shortages result in degradation of stream quality. One of the most critical problems is a lack of sufficient water in the stream to flush and dilute contaminants in the channel. Wastes from upstream discharges can build to the extent that reduced flows available downstream become unusable. Dissolved-solids concentrations are used to indicate the quality of water resources. As concentrations increase with drought, water acquires an unpleasant taste and becomes unsuitable for sensitive industrial processes (6).

Oxygen deficiency is also a characteristic of prolonged low flows. Less flow means less water to assimilate oxygen-demanding wastes. Insufficiency of oxygen can be lethal to fish and other aquatic life, cause odor problems, and decrease a stream's natural ability to purify itself. Generally, the shallow water created by low streamflow becomes warmer than usual and stream temperatures downstream from depleted reservoirs are higher during a drought because less cool water is released from storage. Increased water temperatures can seriously damage aquatic life. Evaporation increases, which further decreases the limited supply of surface water (6).

In coastal zones, fresh water in streams and aquifers flows into and holds back seawater. Decreased streamflow and additional withdrawals of ground water in these areas increase the inland movement of salt water. This further threatens aquatic life which depends upon minimum fresh-water environments (6).

Impact of drought on agriculture tends to become noticeable in the spring. Farmers are forced to delay plowing and seeding because of dry conditions, or seeded crops are damaged by lack of moisture. Commonly there is loss of rich soil in the spring due to the combined forces of wind and drought. As drought continues, range lands are also affected, and ranchers are forced to liquidate herds or to purchase feed to maintain their stock. Many farmers are forced to haul water, and water supplies become increasingly scarce after periods of protracted drought (6).

Fish and wildlife resources are severely affected by drought. In many places, water in streams and estuaries is insufficient for spawning by various species of fish. In other areas, streams, ponds, and even reservoirs may dry up, killing the entire fish population. In many wetland areas, normal forage may not be available for maintaining wildlife and migrating waterfowl (6).

Fire hazards, both urban and rural, greatly increase during dry periods. In urban areas, firefighting can significantly reduce water supplies. Forests may be closed during drought in the interest of fire prevention. This can seriously affect employment in the logging industry. Grassland fires can also be very destructive (20).

Health is another important consideration when dealing with drought. Low water supplies can easily become contaminated and must be closely monitored. Farm families often have to boil water when wells become low and somewhat stagnant. City water systems must be carefully checked at these times, particularly when water pressure is low or is temporarily lost (20).

Local initiative is the key to drought management. The weight of responsibility on local officials and individuals is great. Federal agencies have likewise taken steps to assist states and counties. Water from Federal reservoirs has been released on schedules which contribute to the best management of fish and wildlife (20).

Programs to conserve water are not simple. Once the facts about supplies are clearly established and the feasibility of possible transfers is known, the success of such a program depends on how well the full participation of the public is motivated and achieved. A conservation program that is not well planned can backfire on those responsible. At its best, a water conservation program can access a vast reservoir of ingenuity. Water users must feel that they are fairly treated, that everyone is asked to save, and that sacrifices are felt proportionately (20).

When considering the impact of possible conservation measures, it is significant that a high percentage of water use is for irrigation. While potential savings from conservation programs directed at irrigated agriculture are great, they may not achieve quick results. Many of the techniques for saving water require that farmers and irrigation districts invest heavily in improving and altering their systems (20).

The operation of canals and laterals usually results in some waste because flows do not always equal demand. And, leakage in older systems is significant, amounting to one-fourth or more of diversions. Only the most urgent steps could be taken to modernize old systems in time to achieve savings during a current drought. Others require investments which would have effect over a period of 10 to 15 years (20).

Residential water conservation may enable communities to carry on most normal activities while avoiding the great cost of hauling water, building pipelines, or taking other major steps. In Texas, per capita consumption of water is estimated at about 160 gallons a day. An effective conservation program should be able to halve this consumption without undue hardship by reducing water used in activities such as lawn sprinkling, car washing, and indoor consumption (20).

In addition to voluntary conservation measures and rationing, efforts are usually made to tap new water supplies and to redevelop old ones. Thousands of new wells are drilled, and old wells are deepened to provide relief to domestic, municipal, industrial, and agricultural users. But relief from drought comes only from rainfall. Water managers concerned with reservoir storage or well-field operations may require a year or longer to recover supplies after a period of normal precipitation begins (6).

Minimizing the effects of future droughts requires a better understanding of existing water supplies, anticipated water needs, and current water use. More efficient use must be made of existing water resources. Like energy, some supplies are being utilized that will not be replaced. Unlike energy, other supplies of water can be predictable in quantity, quality, and location. Skillful planning will be required to evaluate tradeoffs among competitive users.

An important impediment to building better water supply systems is the scarcity of information available on the economics and sociology of drought. Responses to drought require careful observation and analysis. This would lead to better knowledge of economic and social impacts, how they are shifted throughout the society, and on whom they ultimately fall. Solutions imposed during water shortages should be as near optimal approaches for the community as knowledge and experience permits (20).

The concept of water conservation has become more acceptable in 1976 and 1977 in those states experiencing protracted drought. Water managers have learned how various sectors respond to water conservation, how large reductions can be, how to enforce compliance, and how to establish goals. California data compared quantities of water used in 1976 and 1977 by 35 major municipal and industrial water districts throughout the State. The average rate of reduction was about 20 percent, with one district reducing 53 percent and another 46 percent. These larger figures represent savings by communities in dire straits and involved an appreciable change in life style. The 20-percent figure apparently represents savings that might be attained by volunteer water conservation efforts (40).

Industries in California also found it possible to cut back on water use. A survey was conducted of 6,000 specialized industries to determine their reaction to water shortages. Preliminary results indicate that few industries would shut down or relocate due to reduced water supplies. Most would use alternative methods of production, and some would reduce production. A reduction of 25 percent in water seemed to have little effect (40).

Farmers can conserve water, but not so readily as municipal and industrial users. Essentially the same agricultural acreage was irrigated in California in 1977 as in 1976 with 15 percent less water. When adequate water is not available, farmers tend to put off salt leaching, use better water control, maintain perennial crops, and switch to crops using less water. Longer-range programs include drip and sprinkler irrigation equipment and increased promotion of irrigation management services (40).

Research and development programs are underway to help meet future water needs.

Water Conservation and Augmentation

The United States has been extravagant and even wasteful in its use of water. As population continues to grow, the magnitude and duration of water shortages will be experienced more frequently and over larger areas. Some of the shortages will be hastened by drought (13).

Water is a finite resource, and the abilities of governments to deliver it are also finite. But the experiences in many places during recent droughts prove that people can live abundant lives with considerably less water than they have been using. Wise water use dictates the need to know quantitatively the availability of water and how it is used. Total withdrawals of water have increased 12 percent nationally since 1970 and have more than doubled since 1950. Further increased demands are anticipated for energy, industrial, residential, and commercial uses. These demands will be met from an already overcommitted water supply by transfer from one type of use to another, by more efficient use, and by reuse (13).

Our past has included two conservation ethics. One is conservation of nature and life in natural settings. The other is conservation of resources that can be used in economic processes. In the history of our country, both of these views have played important roles with either one or the other being dominant depending on conditions. Even the early concepts recognize a need to husband resources by reducing waste, cutting destructive uses of perishable resources, and engaging in the long-term planning of resource availability and usage. The emphasis is not on esthetic beauty but on frugality and efficiency of production and use (22).

A goal to conserve must be accepted and accomplished by the people themselves. At present we are in a traditional phase in which societies' reaction to perceived shortage is to attempt increasing supply while reducing short term demand. Permanent reduction of demand through various conservation measures may well be the primary path of the future. The transition from an ethic of growth to one of conservation can have significant repercussions throughout the economy (22).

Conservation programs are normally constructed as a set of loosely linked initiatives within industrial and consumption processes. The changes are usually private actions outside the control of the public sector. Whenever conservation has been suggested as a policy, the public sector's proposed contribution is usually general research, demonstration programs, educational efforts, and financial risk sharing. It usually has not included regulatory or enforcement actions within an overall program. Since the public role is one of convincing rather than regulating, it must be sensitive to the appropriate strategies. Developed societies tend to have highly mechanized water using industries and include considerable equipment for personal consumption. These may require well developed, capital intensive networks for transportation and product distribution. There may be numerous opportunities for intervention to save the resource (22).

The specific structure develops over a long period of time and depends on many factors. House and Williams (22) find that cultures develop by exploiting resources that are most abundant to them. Therefore, the most immediate reaction to shortages in previously plentiful materials is an attempt to reduce usage. Most shortages are viewed as short run at first. Demand adjustments are normally made in the context of not changing major parts of the economic and social systems. If the problem is not transitory, the short-run adjustments seldom are sufficient to moderate the problem.

When short-term adjustments fail, the cultural system makes longer term adjustments that continue to maintain cultural expectations. These are normally performed within the commercial area by improved efficiencies of use and by substitutions of more abundant materials. If the scarcity of a critical resource continues and sufficient efficiencies and substitutes do not exist, then a permanent cultural change is necessary in the form of economic or social retrogression. The level of change is determined by historical dependence upon the resource and the degree of the shortage. In a highly developed culture, research and development of new processes often take decades to realize. A conservation strategy must recognize as early as possible, the relative availability of resources in order to stretch out the usage of those with high, historical importance and in greatest scarcity (22).

Improved water conservation practices are both necessary and complementary to other national goals. The many growing apparent crises consistently point to a need for increased conservation. But impediments exist which have considerable force in holding back conservation. Consumer conservation means modifying demands amid conflicting claims and often small savings for individual schemes. In many cases, personal conservation requires an initial investment that appears large compared to possible future savings. Automatic lawn watering systems, for example, conserve by controlling time and amount of watering, but they may not be economic in the short run. Even these savings may disappear if the utility gets a rate change to offset decreased deliveries (22).

When a substantial profit is obtained from adopting a conservation practice, there is little lag in adaptation. If water is in short supply and prices increase, conservation practices become more commonplace. In practice, then, conservation appears as a new public policy and as an economic factor after the shortage has occurred. At these times, conservation is a stopgap measure until the economic system affects either supply or demand (22).

Water shortages can be prevented or alleviated in many ways. Each remedy involves some degree of financial, social, or environmental pain and generates some political opposition. Historically, water resource managers have favored use of ground water, supplemented increasingly with reservoirs. Many economic benefits have derived from impoundment and regulated releases of water from reservoirs. Specific water projects have induced the development they were created to produce (54).

Future water projects tend to have increasing opposition. The amount of water available for storage or diversion is diminished, and prime sites for effective impoundment are scarcer. The economic and environmental cost of projects receive increasing opposition. Water transfers from one region to another face increasing costs, opposition from areas of origin, and the fact that they do not increase the overall supply of water (54).

Many water resource experts stress better management of existing supplies by water rights reform, reducing waste, and greater reuse of water. The chief problem is overcoming the habits and traditions of industries, farmers, and homeowners who demand the continued availability of cheap and plentiful water. There is a compelling need to reform the institutional incentives to waste water (54).

Methods for increasing efficiency in water use include metering, water rights reform, rationing, mandated conservation practices, and pricing strategies. The basic question in a region is whether the amount of water is used to guide or limit growth. If migration and development continue in water-deficit areas, it should be possible to adjust life styles to less water per capita and to higher water costs. Economics can provide the most effective limits to further growth in water-deficit areas. Because precipitation and stream flows can fluctuate so widely, officials must develop a clear and legally sound basis for sharing scarcity when cutbacks are forced by drought (54).

Weather Modification

The Weather Modification Act of 1967 assigned the Texas Water Development Board with responsibility to conduct research and development in the field of weather modification technology. Experiments have been conducted in Texas to evaluate the potential for seeding convective-type cloud systems on the Edwards Plateau and the Texas High Plains (50).

In furtherance of weather modification research in the Texas High Plains, the Board in 1974 entered into an agreement with the U. S. Department of the Interior, Bureau of Reclamation to conduct a segment of the High Plains Cooperative Program (HIPLEX) in Texas. This research program is designed to establish both a verified, working technology and an operational management framework capable of producing additional rain from cumulus clouds in the High Plains States east of the Continental Divide (50).

It is difficult to prove that weather modification activities result in additional water from warm-season cumulus clouds. Successful cloud seeding would result in increased precipitation and runoff within minutes. The amount of rainfall without the cloud seeding is incapable of proof. Yet to establish a claim to the additional water developed, a difference must be proved. In actual practice, it will be necessary to predict the amounts and locations of additional precipitation prior to the seeding in order to effect disposition. Further, the rainfall induced by seeding may be challenged in non-seeded areas as a diversion in natural rainfall patterns and thus a cost to them (7).

Desalting Water

The Office of Water Research and Technology of the Department of the Interior has responsibility to help meet future water needs through relevant research and development programs. The refinement of technologies for desalting sea water and water pumped from saline aquifers is one method. On the basis of unit cost comparisons, a few Texas cities have been identified as having desalting costs that are less than, or about the same as costs for water from conventional sources. This includes water production, transportation, treatment, and processing costs. In addition, for desalting, the cost of brine disposal is included (7).

The present contribution of desalting in meeting Texas' water needs is small because of the general economic advantage of development of fresh-water supplies by conventional methods. In many water-short areas, the economics of desalting may be improving through new technology, increased plant scale, and multipurpose desalting complexes (7).

The feedwater for desalting may be ground water, surface water, or seawater, or it may be recycled wastewater. By using municipal wastewater for feedwater, desalting plants may be incorporated into existing municipal water treatment and distribution systems (7).


Texas waters have been damaged by the discharge of wastes.

Water Quality Management

The development of Texas has contributed to the deteriorating quality of its water resources. Rivers, lakes, and coastal waters have been damaged by the discharge of waste, by polluted runoff from urban, agricultural and resource development, and by erosion and sedimentation. A strategy to achieve cleaner waters and reduce the production of unnecessary pollutants is now under way (35).

The objective of the Federal Water Pollution Control Act of 1972 is to restore and maintain the chemical, physical, and biological integrity of the Nation's waters. To achieve this objective, it is declared that (1) national goals and policies require elimination by 1985 of discharge of pollutants into the navigable waters; (2) wherever attainable, an interim goal of water quality which provides for the protection and propogation of fish, shellfish, and wildlife and which provides that recreation in and on the water be achieved by July 1, 1983; (3) the discharge of toxic pollutants in toxic amounts be prohibited; (4) Federal financial assistance be provided to construct publicly-owned waste treatment works; (5) areawide waste treatment management planning processes be developed and implemented; and (6) a major research and demonstration effort be made to develop technology necessary to eliminate the discharge of pollutants into the navigable waters (50).

The Federal Water Pollution Control Act authorized public participation in the achievement of goals regarding the elimination of discharge of pollutants and the improvement of water quality. Implementation of the Act will change the water requirements per unit product in manufacturing and industrial water-using processes. It will improve the quality of raw water to treatment plants and affect the costs of water use. Each of these factors affects water resources planning methods, water requirements, and water use (50).

Table 6 summarizes the quantities of return flows by basin and by use. Several water resource problems and opportunities are associated with quality of return flows. Water standards include such items as minimum levels of dissolved oxygen in the water and maximum levels of fecal coliform bacteria, chemicals, and toxic materials. Fish kills result from toxic substances or shortages of oxygen in the water. Shellfish are contaminated by domestic wastes. Downstream cities find that water discharged by upstream cities may be unsuitable for bathing or other recreational purposes (50).

Public Law 92-500, Amendments to the Water Pollution Control Act, of 1972 provides for a multitude of approaches to water pollution control. In water quality management, different situations and pollutants call for different types of controls. Pollutants may be monitored and controls initiated in production processes, at the point where effluents are discharged, and in the environment. Approaches to controls include regulations, taxes, and subsidies(50).

Each state is required under P. L. 92-500 to identify and locate all point sources of pollution, such as sewage plant outfalls. The State also must locate all man-created nonpoint source pollution loads and set forth procedures to control these discharges where feasible. These nonpoint source discharges include runoff from urban, industrial, agricultural and forested areas, livestock production, construction and related activities, and mine operations (50).

Water management capabilities and strategies will be developed through economic and social choices. Water quality has become an important social problem, and public choices will be made. One result will be expanded reuse of water when waste treatment is accomplished.

TABLE 6. ANNUAL WATER YIELD FROM RETURN FLOWS BY BASINS, 1974

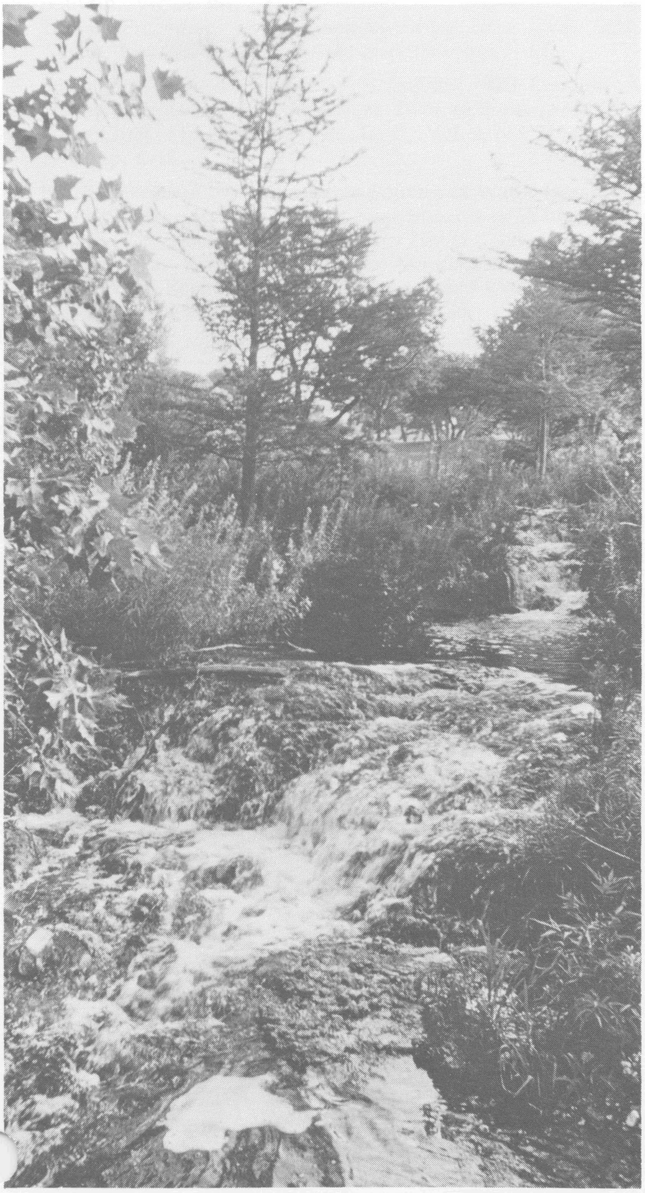
Basin	Municipal & Industrial	Irrigation
	------000's of Acre-Feet[1]------	
Canadian River	17.9	—
Red River	47.3	12.5
Sulphur River	35.4	—
Cypress Creek	148.5	—
Sabine River	252.5	4.0[2]
Neches River	179.1	14.0[2]
Neches-Trinity Coastal	34.0	108.0[2]
Trinity River	346.4	36.1
Trinity-San Jacinto Coastal	25.9	13.0[2]
San Jacinto River	410.0	48.0[2]
San Jacinto-Brazos Coastal	142.0	69.0[2]
Brazos River	156.0	26.6
Brazos-Colorado Coastal	7.0	82.4[2]
Colorado River	65.5	35.0[2]
Colorado-Lavaca Coastal	9.7	75.2[2]
Lavaca River	1.9	113.0[2]
Lavaca-Guadalupe Coastal	8.2	29.0[2]
Guadalupe River	42.2	1.7
San Antonio River	131.6	4.0
San Antonio-Nueces Coastal	8.7	1.0
Nueces River	5.0	10.0
Nueces-Rio Grande Coastal	61.1	—
Rio Grande River	56.6	79.0[2]
Total	2,192.5	761.5

[1]One acre-foot = 325,851 gallons.

[2]Released too far downstream to be considered a part of the surface-water supplies.

Source: Texas Department of Water Resources. Letter from Herbert W. Grubb, Director, Planning and Development, June 12, 1978.

Implications



Efficient use of water can be achieved in many ways.

Texas can be classified as a water deficit state since use exceeds replenishment. The deficit is occurring due primarily to ground-water mining on the High Plains.

Many areas have little excess water to support the environment and economy of the future. Historically, water resource managers have considered it desirable to provide additional water by impoundment and regulated releases from a reservoir, particularly during a drought. But such projects increasingly have become part of the problem. They induce further development, so that additional supplies are claimed even as the projects are built.

Federal funds for multipurpose reservoirs will be much less available in the future. Project costs are rising rapidly. Enlarging the State water development fund requires a constitutional amendment, but voters have defeated two such amendments.

Future water projects based on large reservoirs also face problems for more clearly pragmatic reasons. The amount of water available for storage or diversion is diminished. Prime sites for effective impoundment are scarcer. Reservoirs increase evaporation and seepage losses. The costs of projects weigh heavily. Environmental impacts are substantial in the flood plain and in the estuaries which are often deprived of necessary fresh-water inflows.

Comparing water use to availability for Texas provides some serious implications. Agriculture is by far the largest user of the limited available quantities of water in Texas. The impact of changes in availability (ground-water depletion) and water costs will affect agricultural irrigation much more than any or all other classes of uses taken together. The acres irrigated and level of irrigation per acre will gradually decline, impacting throughout the High Plains and Texas economy.

As municipalities, industries, and environmental requirements continue to expand, water use in all areas of the State will begin to press against availability. As irrigated regions are expected to adjust quantity of water applied and irrigated acreage, other users will be placed in a position of adjustment of water use. Texas has already reached the point where effective and efficient use of water is most important.

To maximize beneficial use of water, optimum application techniques and processes for water conservation should be implemented, and waste should be avoided. Water should be reused to the maximum extent feasible.

Water-saving opportunities exist throughout the State. Since conditions vary from place to place, specific opportunities must be identified individually. The greatest potential savings are found in areas where return flows from excess water applications are released without serving further beneficial use. In other areas, where water conservation measures will not save large quantities of water, they may result in energy savings and offer opportunities for environmental improvement through changes in water management.

More efficient use of water can be achieved in many ways. They include mandated conservation practices — water rights reform, metering, rationing, and pricing strategies. Because agriculture accounts for such a large share of water consumption, the potential for conservation in that area is great. There are equipment changes such as automated distribution systems, computerized scheduling systems, and consulting services to help achieve savings.

On the industrial and municipal side, the potential for water conservation also is significant. An effort should be made to arrange a sequence of uses and reuses of water where possible. Detection and control programs can correct the many leaks, defective connections, and conveyance losses that cause water losses in some municipal distribution systems.

At the domestic level, the opportunities are similarly numerous and varied. Installation of water-saving fixtures and appliances can be accelerated by appropriate plumbing code amendments and promotional efforts. Automatic flow regulators can reduce consumption for shower, kitchen sink, and other uses.

Texas water problems are more complex than just supply. The development and use of Texas aquifers has not been without cost. Problems have included declining water levels, land surface subsidence, salt water intrusion, water quality impairment from surface and subsurface disposal of wastes, and increasing costs of ground water pumping. Legal and institutional arrangements for administration of all surface and ground water sources would be complex. Although such management is possible and has been implemented elsewhere, it has not been attempted in Texas. A successful ground-water management program requires each water user to give up independence of action in order to achieve a common benefit. This may not be possible until the water crisis becomes more severe.

Water is a very sensitive issue in Texas. The demand for limited quantities that are available is increasing and now includes an environmental component. A revised water management policy is necessary for Texas if the water resources are to be used in a manner that will result in the greatest long-term benefit to the people of the State.

Water resources already developed should be used to the maximum extent before new sources are developed. All alternative sources of supply should be considered. Conjunctive use of surface and ground water supplies and storage capacity, including planned temporary overdrafting of ground water, should be utilized to maximize yield and improve water quality. Lastly, and perhaps most important, more effective use of water in Texas with emphasis on reuse and conservation are indicated as viable approaches for meeting much of Texas' future water demands.

References

1. Benton, Arthur R., et. al., *Monitoring of Texas Coastal Wetlands,* Remote Sensing Center Technical Report RSC-88, Texas A&M University, College Station, August 1977.

2. Booth, Frank R., "Adjudication of Water Rights," in *Water... and the New Texas Law,* Proceedings of Institute Held Jointly by Laredo Bar Association and State Bar of Texas, Laredo, Texas, January 19, 1968, pp. 1-83.

3. Booth, Frank R., "Alternative Ground Water Laws for Texas," *Proceedings of the 1974 Conference on Water For Texas,* sponsored by Texas Water Resources Institute, Texas A&M University, College Station, September 19-20, 1974, pp. 29-60.

4. Boswell, Howard, "The Conflict, Real and Apparent, Between Soil Conservationists and Water Users," *Proceedings of Water Law Conference, May 25-26, 1956,* University of Texas School of Law, Austin, pp. 100-103.

5. Bouldin, Victor W., "Rights in Diffused Surface Water in Texas," *Proceedings of Water Law Conference, June 17-18, 1955,* Austin, University of Texas School of Law, pp. 5-14.

6. Buchanan, Thomas J. and Bruce K. Gilbert, "The Drought: A Pervasive Problem," *Water Spectrum,* Dept. of the Army, Office of the Chief of Engineers, Wash., D. C., Vol. 9, No. 3, Summer 1977, pp. 6-12.

7. Butcher, William S., "Alternative Sources of Water-Desalting, Cloud Seeding and Developing New Sources of Water," *Proceedings of a Conference on Future Water Use in Texas,* sponsored by the Texas Water Conservation Association, Austin, and Texas Water Resources Institute, Texas A&M University, College Station, October 14-15, 1976, pp. 25-35.

8. Calhoun, Ron, "Stricter Water Rate Controls May Be Sought by Lawmaker," *Dallas Times Herald,* Dec. 21, 1977.

9. Carr, John T., Jr., *The Climate and Physiography of Texas,* Report No. 53, Texas Water Development Board, Austin, July 1967.

10. Colette, W. Arden, *The Conceptualization and Quantification of a Water Supply Sector for a National Agricultural Analysis Model Involving Water Resources,* The Center for Agricultural and Rural Development, Miscellaneous Report, Iowa State University, Ames, April 1976.

11. Condra, Gary D., Ronald D. Lacewell, J. Michael Sprott and B. Michael Adams, *A Model for Estimating Demand for Irrigation Water on the Texas High Plains,* Texas Water Resources Institute Technical Report 68, May 1975.

12. Cook, Earl, "Some Economic and Decision Aspects of the Canyon Project," *Reservoir Impact Study,* Final Report to the Office of Water Resources Research, U. S. Dept. of the Interior, College of Geosciences, Texas A&M University, Nov. 1974.

13. Cragwall, Joseph S., *Establishing Water Priorities Requires a Good Data Base,* for presentation at the Water Resources Management Conference, Madison, Wisconsin, October 3, 1977.

14. Cronin, J. G., *Ground Water in the Ogallala Formation in the Southern High Plains of Texas and New Mexico,* U. S. Geological Survey, Hydrologic Investigation, Atlas No. 339, Wash., D. C., U. S. Govt. Printing Office 1969.

15. Environmental Protection Agency, *Federal Register,* Vol. 42, No. 189, Sept. 29, 1977, pp. 51575-51579.

16. Environmental Protection Agency, *Support Document, EPA Determination of the Edwards Underground Reservoir,* Gonzalez Amendment.

17. Goldsum, John, "Environmental Constraints and Industrial Water Use," *Proceedings of a Conference on Future Water Use in Texas,* sponsored by the Texas Water Conservation Association, Austin, and Texas Water Resources Institute, Texas A&M University, College Station, October 14-15, 1976, pp. 77-83.

18. Graeser, Henry, "Good Management for Maximum Utilization," *Proceedings of a Conference on Future Water Use in Texas,* sponsored by Texas Water Conservation Association, Austin, and the Texas Water Resource Institute, Texas A&M University, College Station, October 14-15, 1976, pp. 9-14.

19. Guyton, William F., "Technological Limitations to Ground Water Management," *Proceedings of the 1974 Conference on Water For Texas,* Texas Water Resources Institute, Texas A&M University, College Station, Sept. 19-20, 1974, pp. 113-120.

20. Harrison, Robert, "Response to Drought," *Water Spectrum,* Dept. of the Army, Office of the Chief of Engineers, Wash., D. C., Vol. 9, No. 3, Summer 1977, pp. 34-41.

21. High Plains Underground Water Conservation District No. 1, "Water Import Results Reviewed," *The Cross Section,* Vol. 19, No. 8, Lubbock, August 1973.

22. House, Peter W. and Edward R. Williams, *Planning and Conservation – The Emergence of the Frugal Society,* Praeger Special Studies, 200 Park Avenue, N. Y., N. Y., 1977.

23. Hughes, William F. and Wyatte L. Harman, *Projected Economic Life of Water Resources, Subdivision Number 1 High Plains Underground Water Reservoir,* Texas Agricultural Experiment Station Technical Monograph 6, December 1969, p. 75.

24. Huston, R. J., "Factors Related to Water Use as a Coolant," *Proceedings of a Conference on Future Water Use in Texas,* sponsored by the Texas Water Conservation Association, Austin, and Texas Water Resources Institute, Texas A&M University, College Station, October 14-15, 1976, pp. 39-48.

25. Hutchins, Wells A., *The Texas Law of Water Rights,* Austin: Texas Board of Water Engineers, 1961.

26. Kelso, M. M., Principal Investigator, *Economic Implication of Public Water Policy in Arizona,* The University of Arizona, Tucson, October 1974.

27. Lacewell, R. D., G. D. Condra, and B. Fish, "Impact of Energy Cost on Food and Fiber Production," Paper presented to Water for Texas Conference, College Station, Texas, March 1976.

28. Lambert, Waller P. and E. Gus Fruh, *A Methodology for Investigating Fresh Water Inflow Requirements of a Texas Estuary,* Center for Research in Water Resources, The University of Texas at Austin, 1976.

29. McDaniels, Louis L., *Conservation Storage Reservoirs in Texas – Some Aspects and Chronology of Surface-Water Resources Development,* Texas Water Commission Bulletin 6404, Austin, Texas, April 1964.

30. McNeely, John G., *Rural Land Resource Problems... A Need For Planning,* Texas Agricultural Experiment Station MP-1190, May 1975.

31. McNeely, John G. and Ronald D. Lacewell, *Flood Plain Management,* Texas Agricultural Experiment Station Bulletin 1166, November 1976.

32. McNeely, John G. and Ronald D. Lacewell, *Surface Water Development in Texas,* Texas Agricultural Experiment Station Bulletin 1177, May 1977.

33. Milne, Murray, *Residential Water Conservation,* California Water Resources Center Report No. 35, University of California, Davis, March 1976.

34. Moseley, Joe C., II, "Impact of Bays and Estuaries on Food Demand in the State and Nation," *Proceedings of the TAMU Centennial Year Water For Texas Conference,* Texas Water Resources Institute, Texas A&M University, College Station, Texas, March 25-26, 1976.

35. National Water Commission, *Water Policies for the Future,* Final Report to the President and to the Congress of the United States, Wash., D. C., June 1973.

36. Price, R. D., D. A. Muller and W. B. Klemt, "Reevaluation of State's Ground-Water Resources Completed," *Water For Texas,* Vol. 6, No. 2, Feb. 1976.

37. Rayner, Frank A., "Government and Ground Water Management," *Proceedings of the 1974 Conference on Water For Texas*, sponsored by the Texas Water Resources Institute, Texas A&M University, College Station, Sept. 19-20, 1974. pp. 145-173.

38. Rehder, Helmut J., *The Evolution of Integrated Water Resources Development: Concept and Application*, M.S. Thesis, The University of Texas, May 1965.

39. Richardson, Gene, "Conservation of Water For Future Needs — Agency Planning," *Proceedings of a Conference on Future Water Use in Texas*, sponsored by the Texas Water Conservation Association, Austin, and Texas Water Resources Institute, Texas A&M University, College Station, Oct. 14-15, 1976, pp. 143-146.

40. Robie, Ronald B., "Water Issues Facing California," Department of Water Resources, The Resources Agency, State of California, presentation in the Lecture Series of the Institute of Governmental Studies, University of California, Berkeley, January 19, 1977 (Updated and expanded as of Sept. 1977).

41. Ruesink, Lou Ellen, "Old Beyond Years," *Texas Water Resources*, Vol. 4, No. 1, Texas A&M University, College Station, Feb. 1978.

42. Skrabanek, R. L., "Estimates of the Population of Texas Counties and Metropolitan Areas: July 1, 1975 (Revised) and 1976 Provisional," *Population Estimates and Projections*, Series P-25, No. 717, U. S. Dept. of Commerce, Bureau of the Census, January 1978.

43. Sloggett, Gordon, *Mining The Ogallala Aquifer: State and Local Efforts in Groundwater Management*, Agricultural Experiment Station — USDA Research Report P-761, Oklahoma State University, November 1977.

44. Templer, Otis W., *Institutional Constraints and Conjunctive Management of Water Resources in West Texas*, WRC-76-1, Water Resources Center, Texas Tech University, Lubbock, Texas, Feb. 1976.

45. Templer, Otis W., *Water Law and the Hydrologic Cycle, A Texas Example*, Water Resources Bulletin IX, No. 2, April 1973, pp. 273-283.

46. *Texas Almanac*, Dallas: A. H. Belo Corporation, 1974.

47. Texas Department of Water Resources, "Analytical Study of the Ogallala Aquifer in Hockley County, Texas," *News Release*, Report 214, Austin, Texas, January 10, 1978.

48. Texas Society of Professional Engineers and Texas Section of the American Society of Civil Engineers, *The Effects of Ponds and Small Reservoirs on the Water Resources of Texas*, Austin, The Society, 1974.

49. Texas Water Development Board, "Board's Construction Policy Unchanged," *Water For Texas*, Vol. 5, No. 6, June 1975, p. 9.

50. Texas Water Development Board, *Continuing Water Resource Planning and Development for Texas*, Vol. 1 and 2, Draft Report, Austin, Texas, May 1977.

51. Texas Water Development Board, *Dams and Reservoirs in Texas*, Parts I, II and III, Report No. 126, Austin.

52. Texas Water Development Board, *Laws and Programs Pertaining to Texas Land and Water Resources*, The Board, Report No. 89, Austin, Dec. 1968.

53. Texas Water Rights Commission, *Thirty-First Report of the Texas Water Rights Commission, Covering the Biennium September 1, 1972 through August, 31, 1974*, The Commission, Austin, 1972.

54. The Conservation Foundation, Rice Odell, Editor, "Though Remedies Abound, Water Problems Persist," *Conservation Foundation Letter*, 1717 Massachusetts Ave., N.W., Wash., D. C., May 1977.

55. The Conservation Foundation, Rice Odell, Editor, "Water Outlook: As Uncertain As the Weather," *Conservation Foundation Letter*, 1717 Massachusetts Ave., N.W., Wash., D. C., April 1977.

56. The Resources Agency, State of California, *Water Conservation in California*, Department of Water Resources Bulletin No. 198, May 1976 (Reprinted March 1977).

57. Van Dyke, Robert, "Ground Water Management in the Metropolitan Areas," *Proceedings of the 1974 Conference on Water For Texas*, sponsored by the Texas Water Resources Institute, Texas A&M University, College Station, September 19-20, 1974, pp. 131-135.

58. Victory, Frances, "Leaky Water Mains Plague Homeowners, City," *The Houston Post*, January 8, 1978, p. 3A.

59. Williams, Jean, "Ground Water Management Potentials," *Water For Texas*, II, No. 6, June 1972, pp. 4-6.

60. Williams, Jean, "Issues of Ground Water Management in the Coastal Zone," *Proceedings of the 1974 Conference on Water For Texas*, sponsored by the Water Resources Institute, Texas A&M University, College Station, Sept. 19-20, 1974, p. 123-130.

61. Wilson, Jim, "The Effect of Recycling on Water Use and Legal PROBLEMS OF Re-Allocation," *Proceedings of a Conference on Future Water Use in Texas*, sponsored by the Texas Water Conservation Association, Austin, and Texas Water Resources Institute, Texas A&M University, College Station, October 14-15, 1976, pp. 129-134.

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